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(71) Applicant (*for all designated States except US*): **HALEOS, INC.** [US/US]; 3150 State Street, Blacksburg, VA 24060 (US).

(72) Inventors; and
(75) Inventors/Applicants (*for US only*): **STEINBERG, Dan, A.** [US/US]; 410 Lee Street, Blacksburg, VA 24060 (US). **RASNAKE, Larry, J.** [US/US]; 1315 Sandy Circle, Blacksburg, VA 24060 (US).

(74) Agents: **CHILD, John, S., Jr., Esquire** et al.; DANN DORFMAN HERRELL AND SKILLMAN, Suite 720, 1601 Market Street, Philadelphia, PA 19103-2307 (US).

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(54) **Title:** ETCHING PROCESS FOR MICROMACHINING CRYSTALLINE MATERIALS AND DEVICES FABRICATED THEREBY

(57) **Abstract:** The present invention provides an optical microbench having intersecting structures etched into a substrate. In particular, microbenches in accordance with the present invention include structures having a planar surfaces formed along selected crystallographaich planes of a single crystal substrate. Two of the structures provided are an etch-stop pit and an anisotropically etched feature disposed adjacent the etch-stop pit. At the point of intersection between the etch-stop pit and the anisotropically etched feature the oreintation of the crystallographic planes is maintained. The present invention also provides a method for micromachining a substrate to form an optical microbench. The method comprises the steps of forming an etch-stop pit and forming an anisotropically etched feature adjacent the etch-stop pit. The method may also comprise coating the surfaces of the etch-stop it with an etch-stop layer.

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ETCHING PROCESS FOR MICROMACHINING CRYSTALLINE MATERIALS AND DEVICES FABRICATED THEREBY

FIELD OF THE INVENTION

The present invention relates generally to devices having intersecting structures etched into a substrate and a method for making such devices, and more specifically to structures having a planar surface formed along a selected crystallographic plane of a single crystal substrate, where the method provides that such a surface retains a selected planar orientation at the point of intersection of such a surface with surfaces of additional structures in the substrate so that, for example, perfect convex corners are maintained.

BACKGROUND OF THE INVENTION

The ability to precisely locate optical elements relative to one another is of critical importance in the fabrication of micro-optical devices, since the alignment tolerances between elements are often specified in submicron dimensions. Typically, such elements may include an optical signal source, such as a laser, a detector, and an integrated or discrete waveguide, such as a fiber-optic or GRIN rod lens. Additionally, such elements may include a fiber amplifier, optical filter, modulator, grating, ball lens, or other components for conveying or modifying an optical beam. Micro-optical devices containing such components are crucial in existing applications such as optical communication and consumer opto-electronics, as well as applications currently being developed, such as optical computing.

Maintaining precise alignment among the optical elements may be conveniently provided by an optical microbench, such as a silicon optical bench. An optical microbench comprises three-dimensional structures having precisely defined surfaces onto which optical elements may be precisely positioned. One material well-suited for use as an optical microbench is single crystal silicon, because single crystal

silicon may be etched anisotropically to yield three-dimensional structures having planar sidewalls formed by the precisely defined crystallographic planes of the silicon. For example, the {111} silicon plane is known to etch more slowly than the {100} or {110} planes with proper choice of etchant. Thus, structures may be formed comprising walls that are {111} planes by anisotropic etching.

Since the optical elements sit within the three-dimensional structures at a position below a top surface of the silicon substrate, a portion of the optical path often lies below the top surface of the substrate, within the volume of the substrate. Accordingly, passageways must be provided in the optical microbench between three-dimensional structures so that light may travel between the elements disposed in the associated three-dimensional structures. Hence, an optical microbench should contain three-dimensional structures that communicate with one another through structures such as a passageway.

While discrete, non-communicating, three-dimensional structures may be conveniently formed by an isotropic etching, etched structures which communicate with one another at particular geometries, such as a convex corner, pose significant problems for applications in which it is desirable to maintain the precise geometry defined by the crystallographic planes. For example, where two {111} planes intersect at a convex corner, the convex corner does not take the form of a straight line intersection between two planes, but rather rounds to create a rounded intersection between the two {111} planes. As etching continues to reach desired depth of the structure containing the {111} planes, the rounding of the corners can grow to such an extent that a substantial portion of the intersection between the two {111} planes is obliterated. Since the {111} planes are provided in the three-dimensional structures to form a planar surfaces against which optical elements may be precisely positioned, absence of a substantial portion of the {111} planes at the intersection can introduce a great deal of variability of the positioning of the elements at the intersection. Thus, the benefits provided by the crystallographic planes can be unacceptably diminished.

Traditionally, to avoid etching intersecting features, dicing saw cuts may be used. However, dicing saw cuts can be undesirable, because such cuts typically must extend across the entire substrate and may not conveniently be located at discrete locations within the substrate. Moreover, dicing saw cuts create debris which may be deposited across the substrate surface and lodge within the three-dimensional

structures, which may interfere with the precise positioning of optical elements within such a structure.

Therefore, there remains a need in the art for optical microbench technology which permits three-dimensional structures having crystallographic planar surfaces to intersect with other surfaces, without degrading the crystallographic orientation of the intersected planar surfaces.

SUMMARY

The present invention provides an optical microbench comprising a substrate having an etch-stop pit and an etched feature, such as an anisotropically etched feature, disposed adjacent the etch-stop pit. The anisotropically etched feature may comprise a V-groove. The etch-stop pit may have a shape suited to supporting an etch-stop layer on the surfaces of the etch-stop pit. The etch-stop pit may be created prior to creating the etched feature. The etch-stop layer comprises a material resistant to the etchant which is used to create the etched feature. After the etch-stop layer is provided, the etched feature is etched in the substrate. The etch-stop layer prevents the feature etching from extending into the region where the etch-stop pit is located. The prevention of such etching by the etch-stop layer provides that the crystallographic planner walls of the anisotropically etched feature maintain their crystallographic orientation adjacent the stop-etch pit.

The present invention also provides a method for micromachining a substrate to form an optical microbench. The method comprises the steps of forming an etch-stop pit and forming an anisotropically etched feature adjacent the etch-stop pit. The method may also comprise coating the surfaces of the etch-stop pit with an etch-stop layer.

BRIEF DESCRIPTION OF THE DRAWINGS

The foregoing summary and the following detailed description of the preferred embodiments of the present invention will be best understood when read in conjunction with the appended drawings, in which:

Figure 1 schematically illustrates a top view of a V-groove provided in an upper surface of a substrate, where the V-groove includes two ends which include wedge-shaped end portions;

Figures 34, 35A, 36, and 37 schematically illustrate top views of substrates having a U-shaped etch-stop pit adjacent to a V- pit to provide a location on the substrate for a laser mount and to provide a location for retaining a spherical optical element;

Figure 35B schematically illustrates a cross-sectional view of the substrate illustrated in Figure 35A;

Figures 38A and 39A schematically illustrate top views of substrates having a V-groove with an etch-stop pit and fiber stop disposed internally to the groove;

Figures 38B and 39B schematically illustrate cross-sectional views of the substrates illustrated in Figures 38A and 39A, respectively;

Figures 40 illustrates a flowchart representing a process in accordance with the present invention for creating an etch-stop pit and an adjacent anisotropically etched feature;

Figures 41 illustrates a flowchart representing another process of the present invention for creating an etch-stop pit and adjacent an anisotropically etched feature;

Figures 42 illustrates a flowchart representing yet another process of the present invention for creating an etch-stop pit and an adjacent anisotropic feature;

Figures 43 and 44 schematically illustrate a top view and a cross-sectional view, respectively, of a substrate comprising a V-groove and an adjoining etch-stop pit;

Figures 45-51 schematically illustrates cross-sectional views of a substrate at selected steps of processing in accordance with the method illustrated in the flowchart of Fig. 41;

Figures 52-58 schematically illustrates cross-sectional views of a substrate at selected steps of processing in accordance with the method illustrated in the flowchart of Fig. 42; and

Figures 59-64 schematically illustrates cross-sectional views of a substrate at selected steps of processing in accordance with the method illustrated in the flowchart of Fig. 43.

Figures 2A-2D schematically illustrate top views of a substrate showing the changes to the substrate as features are added to the substrate to create a structure having a V-groove and an adjoining etch-stop pit in accordance with a first embodiment of the present invention;

Figures 3A-3F and 4A-4D schematically illustrate top views of alternative etch-stop pit configurations with the adjoining V-grooves in accordance with the present invention;

Figure 5 schematically illustrates a top view of an alternative etch-stop pit configuration in accordance with the present invention for preventing formation of a wedge-shaped end wall in a V-groove;

Figure 6 schematically illustrates a top view of an alternative etch-stop pit configuration in accordance with the present invention for providing a partial, wedge-shaped end wall in a V-groove;

Figure 7 schematically illustrates a top view of an alternative etch-stop pit configuration in accordance with the present invention for preventing formation of a wedge-shaped end walls in three V-grooves which adjoin the etch-stop pit;

Figures 8-10 schematically illustrate top views of further configurations of etch-stop pits and V-grooves along with a device mount for providing optical subassemblies in accordance with the present invention;

Figures 11-16 schematically illustrate top views of alternative configurations etch-stop pits with two or more V-grooves adjoining the etch-stop pits;

Figures 17-20 schematically illustrate top views of substrates having etch-stop pits, V-grooves, and an optional V-pit, for providing optical subassemblies in accordance with the present invention;

Figures 21-26 schematically illustrate top views of substrates having two V-grooves oriented at 90 degrees with respect to one another and having an etch-stop pit disposed at the location of the intersection of the two V-grooves;

Figures 27 and 28 schematically illustrate top views of substrates having an etch-stop pits disposed at locations where an inside, convex corner of two intersecting V-grooves would be located;

Figures 29A-29D, 30, 31, 32A-32B, and 33 schematically illustrate top views of substrates having an etch-stop pit which circumscribes a selected area of the substrate in which an anisotropically etched feature is formed;

DETAILED DESCRIPTION OF THE INVENTION

Referring now to the figures, wherein like elements are numbered alike throughout, several different embodiments of devices in accordance with the present invention are illustrated. The different embodiments include a substrate having at least two common features, an etch-stop pit and an anisotropically etched feature adjacent the etch-stop pit. The etch-stop pit has a shape suited to supporting an etch-stop layer on the surfaces of the etch-stop pit. The etch-stop pit is created prior to creating the anisotropically etched feature. The etch-stop layer comprises a material resistant to the etchant which is used to create the anisotropically etched feature. After the etch-stop layer is provided, the anisotropically etched feature is etched in the substrate. The etch-stop layer prevents the anisotropic etching from extending into the region where the etch-stop pit is located. The prevention of such anisotropic etching by the etch-stop layer provides that the crystallographic planner walls of the anisotropically etched feature maintain their crystallographic orientation adjacent the stop-etch pit. The advantages of preventing such etching are illustrated in the accompanying figures depicting several desirable embodiments of the present invention.

Throughout the figures, the substrate material is selected to be <100>-oriented silicon. However, other orientations of silicon, such as <110>-oriented silicon, may also be used in accordance with the present invention. In addition, other anisotropic crystalline materials, such as III – V semiconductor materials, e.g., InP, GaAs, InAs, or GaP, may be used in accordance with the present invention. The substrate material is chosen with regard to the nature of the particular optical device and the features to be fabricated. The crystal orientation of the substrate may be chosen with respect to the desired orientation of the sidewalls of the fabricated features. For example, <100>-oriented silicon may be selected to create a features having sidewalls that are sloped with respect to the upper surface of the substrate. Alternatively, <110>-oriented silicon may be selected to create features having sidewalls that are perpendicular to the upper surface of the substrate.

An example of a typical feature which may be formed by anisotropic etching in an <100>-oriented silicon substrate 6 is a V-groove 2, as illustrated in Fig. 1. In a first aspect of the present invention a modified V-groove 2 is provided, V-groove 12,

having a configuration particularly well-suited to retaining a cylindrical element, such as an optical fiber or GRIN rod lens, as illustrated in Figs. 2A-2D.

Turning first to the V-groove 2 illustrated in Fig.1, each surface of the V-groove 2 is a {111}-plane of the silicon substrate 6. The V-groove 2 may be made by known methods such as etching through a rectangular aperture mask using an aqueous solution of KOH. A V-groove 2 which does not extend to the edges of the substrate 6 includes two wedge-shaped end walls 4. The end walls 4 slope upwardly towards the upper surface 1 of the substrate 6 from an apex 5. A wedge-shaped end wall 4 is often undesirable in optical subassemblies, because a wedge-shaped end wall 4 can partially or completely occlude the optical path to block light transmitted to or from an optical element disposed in the V-groove 2. In addition, the wedge-shaped end wall 4 functions poorly as an optical fiber stop, since the wedge-shaped end wall 4 is sloped with respect to the endface of the fiber which is usually perpendicular to the longitudinal axis of the fiber. Thus, it is desirable to create a V-groove without one or more of the wedge-shaped end walls 4.

In particular, referring to Fig. 2D, a V-groove structure in accordance with the present invention is illustrated where one of the wedge-shaped end walls 14a, shown in phantom, is eliminated from the V-groove 12. The device includes a substrate 10 having an upper surface 11 in which a V-groove 12 and adjacent etch-stop pit 16 are provided. The edges 13 where the V-groove 12 and the stop-etch pit 16 intersect are straight line segments that lie within the {111}-plane of the V-groove sidewalls 15. The ability to remove the right end wall 14a while maintaining the {111}-orientation of the sidewalls 15 in the vicinity of the removed end wall 14a is provided by the etch-stop pit 16 and etch-stop layer 18.

The sequence in which the etch-stop pit 16 and V-groove 12 are formed in the surface of the substrate 10 is illustrated in Figs. 2A-2D. Turning to Fig. 2A, a top elevational view of the substrate 10 is shown in which an etch-stop pit 16 is formed. As depicted, the etch-stop pit 16 has a triangular cross-section in the plane of the upper surface 11 of the substrate 10. Other shapes than triangular cross-section may be used so long as such shapes are suited to preventing the formation of a wedge-shaped end wall 14a of the V-groove 12. The types of shapes which may be used are discussed below with reference to Figs. 3 and 4.

The walls of the etch-stop pit 16 may desirably extend into the substrate 10 at a 90 degree angle, i.e. vertical, relative to the upper surface 11 of the substrate 10, and the etch-stop pit 16 may contain a flat bottom parallel to the plane of the upper surface 11. Such a configuration of the etch-stop pit 16 may be fabricated by high-aspect ratio dry etching, such as reactive ion etching. Alternatively, the etch-stop pit 16 may include sidewalls that are sloped with respect to the plane of the upper surface 11. Regardless of the sidewall slope that is utilized, the portions of the sidewalls 16a located proximate the region at which the V-groove 12 is to be formed, i.e. at intersecting segments 13, should extend into the substrate 10 a greater depth than the depth intended for the adjoining portion of the V-groove 12. Providing such a deeper sidewall portion ensures that a subsequently applied etch-stop layer 18 provides a barrier between an etchant in the V-groove 12 and the etch-stop pit 16.

After formation of the etch-stop pit 16, an etch-stop layer 18 is conformally provided on the sidewalls 16a and the bottom of the etch-stop pit 16. The etch-stop layer 18 comprises a material that is resistant to the etchant that will be used to create the V-groove 12. For example, the etch-stop layer 18 may comprise silicon dioxide, which may be provided by CVD or by thermally oxidizing surfaces 16a of the etch-stop pit 16, or silicon nitride, which may be provided by CVD. Optionally, the upper surface 11 of the substrate 10 may be provided with a layer of the same material used for the etch-stop layer 18.

The V-groove 12 is formed in the surface 11 of the substrate 10 by a suitable process, such as anisotropic wet etching with KOH or EDP through a rectangular aperture mask. The rectangular aperture mask is oriented such that the perimeter of the rectangular aperture is registered to the perimeter of the V-groove 12 located in the upper surface 11 of the substrate 10. The rectangular aperture mask is oriented such that a portion of an end of the rectangular aperture overlies the etch-stop pit 16. Further details regarding how the masks are provided is discussed below in connection with the method of the present invention.

As an optional additional step, the etch-stop layer 18 may be removed from the etch-stop pit 16. Removal of the etch-stop layer allows the V-groove 12 to communicate with the etch-stop pit 16. Such communication permits an element, such as a fiber, disposed within the V-groove 12 to extend into the region over the

etch-stop pit 16 and abut the sidewall 16a of the etch-stop pit 16 that is disposed perpendicular to the longitudinal axis of the V-groove 12, to provide a fiber stop 17.

The process described above with respect to Fig. 2D is suited to forming all of the structures illustrated herein. For example, each of the following structures described below includes at least one etch-stop pit which is formed before an adjacent anisotropically etched feature, such as a V- groove is formed adjacent to the pit. In addition, an etch-stop layer is provided in the etch-stop pit prior to forming a anisotropically etched feature. While the etch-stop layer may not be illustrated in the figures, because it has been removed after the formation of the anisotropically etched feature, it is understood that the etch-stop layer is present within the etch-stop pit while the anisotropically etched feature is being formed.

In addition to the triangular cross-sectional shape of the etch-stop pit 16 illustrated in Figs. 2A-2D, other cross-sectional shapes may be used in accordance with the method of the present invention to completely or partially prevent the formation of a wedge-shaped end wall of a V- groove, as shown in Figs. 3C-3F and 4A-4D. For example, a first type of etch-stop pit configuration for completely preventing the formation of a wedge-shaped end wall 44 is illustrated in Figs. 4A-4D. Figs. 4A-4D illustrate top elevational views of a V-groove 42 adjacent to etch-stop pits 46, 47, 48, 49 of differing cross-sectional areas. In each configuration, the etch-stop pit 46, 47, 48, 49 completely overlays a region of the substrate in which the wedge-shaped end wall 44 of the V-groove 42 would otherwise be formed. The etch-stop pit 46, 47, 48, 49 and V-groove 42 may be formed in the substrate by the procedure described above with respect to the device illustrated in Fig. 2D.

One desirable configuration of an etch-stop pit 49 comprises two sidewalls joined at an apex that lies along the longitudinal axis of the V-groove 42 such that the apex angle, α, is bisected by the longitudinal axis. Such a configuration of an etch-stop pit 49 can prevent the formation of a wedge-shaped end wall 44 when the apex angle is less than or equal to 90 degrees.

If the apex angle were greater than 90 degrees, as illustrated in Figs. 3C and 3D, a partial wedge-shaped end wall 34 would be formed in the V-groove 32. In the configuration where the "apex angle" is equal to 180 degrees, i.e. a straight line, the typical wedge-shaped end wall 24 would be formed in the V-groove 22, as illustrated in Figs. 3A and 3B. That is, an etch-stop pit 26 having a straight sidewall 23 adjacent

to the area in which the V-groove 22, is to be formed, and oriented perpendicular to the longitudinal axis of the V-groove 22, allows for the formation of a wedge-shaped end wall 24. Other cross-sectional shapes of an etch-stop pit are contemplated in accordance with the present invention, such as the "W" cross-sectional shape depicted in Figs. 3E and 3F.

Yet another configuration of an etch-stop pit 386 in accordance with the present invention may be provided so that a fiber stop 387 is created within a V-groove 384, as illustrated in Figs. 38A-38B and 39A-39B. Figs. 38A and 39A illustrated top views of a substrate 380 in which a V-groove 384 is formed. Figs. 38B and 39B illustrate cross-sectional views taken along the lines B – B in Figs. 38A and 39A, respectively. The etch-stop pit 386 has a shape that promotes the formation of a wedge-shaped fiber stop 387 along a {111} crystallographic plane adjacent a first sidewall 383 of the etch-stop pit 386. In particular, the straight sidewall 383 oriented perpendicular to the longitudinal axis of the V-groove 384 promotes the formation of the wedge-shaped fiber stop 387 in an analogous fashion to the formation of the wedge-shaped end wall 24 in Fig. 3B. The etch-stop pit 386 also comprises a pair of angled sidewalls 385 across the dark and 386 from the first end wall 383. The angled sidewalls 385 intersect at a selected apex angle which has a magnitude and orientation suitable for preventing the formation of wedge-shaped surfaces, i.e. {111} surfaces, in the V-groove 384 adjacent to the angled sidewalls 385. The angled sidewalls 385 may have a similar configuration to corresponding sidewalls depicted in Fig. 2D. As illustrated in the cross-sectional views of Figs. 38B and 39B, the wedge- shaped fiber stop 387 extends above the deepest portion of the V-groove 384 so that a fiber 381 disposed within the V-groove 384 may abut the wedge-shaped fiber stop 387.

A second type of etch-stop pit configuration that prevents a wedge-shaped end wall from forming has a parallelogram cross-sectional shape oriented at an angle, β, of 45 degrees or less, with the longitudinal axis of the V-groove 52, as illustrated in Fig. 5. If, the angle, β, is larger than 45 degrees, as depicted in the configuration of Fig. 6, then a partial wedge-shaped end wall 64 is formed in the V-groove 62. In a case where β is 90 degrees, the configuration of the etch-stop pit becomes functionally equivalent to that of the etch-stop pit depicted in Fig. 3A. In addition, V-grooves 52, 53, 55 may be provided on opposing sides of the etch-stop pit 56 as illustrated in Fig. 7. So long as the longitudinal axis of each V-grooves 52, 53, 55 is oriented at an

angle less than 45 degrees relative to an adjacent surface of the etch-stop pit 56, the etching process in accordance with the present invention will not produce wedge-shaped end walls in the V-grooves 52, 53, 55 in the region adjacent the etch-stop pit 56. Any number of V-grooves may be so provided, and such grooves need not have the same size.

Returning now to the configuration illustrated in Fig. 2D, where the combined V-groove 14 and etch-stop pit 16 provide a cavity having a fiber stop 17 for retaining a fiber optic, further optical subassemblies may be fabricated by providing additional features in or on the substrate 10. Such subassemblies may provide for optical communication with the fiber. In particular, the structure of Fig. 2D is well-suited for use with other optical elements, because the fiber stop 17 provides a fiducial reference point to precisely identify where the end of the fiber is located.

For example, Figs. 8-10 illustrate top elevational views of additional configurations in accordance with the present invention that provide optical subassemblies comprising a fiber 81, 91, 101, a V-groove 84, 94 104, and a laser mount 85, 95, 105. Alternatively, detector mounts could be provided in place of the laser mounts 85, 95, 105. In particular, with reference to Fig. 8, a V-groove 84 and adjoining etch-stop pit 86 with fiber stop 83 are provided in a configuration similar to that depicted in Fig. 2D described above. The etch-stop pit 86, however, is not precisely triangular in cross-section, but rather includes an etched area 87 that protrudes, in cross-section, from the fiber-stop edge of the etch-stop pit 86, so that the cross-sectional shape of the etch-stop pit 86 is similar to that of an arrowhead. The etched area 87 allows for beam expansion. In addition, a laser mount 85 is provided proximate the etched area 87 and is disposed along the longitudinal axis of the V-groove 84. It may be desirable to provide an optical device between the end of the fiber optic 81 and the laser mount 85. Accordingly, the configurations illustrated in Figs. 9 and 10 provide slots 99, 109 for receiving optical elements. The slots 99, 109 communicate with the respective etch-stop pits 96, 106 and may be formed at the same time as the etch-stop pits 96, 106. The slots 99, 109 comprise vertical sidewalls, however, sloped sidewalls may also be provided. The slot 109 of Fig. 10 conveniently has a cross-sectional shape of a plano-convex lens, whereas the slots 99 is well-suited to receiving flat optics.

In yet another etch-stop pit configuration in accordance with the present invention, the etch-stop pit may have a diamond-like cross-sectional shape which is suited to device configurations that include two or more V-grooves disposed on opposing sides of the etch-stop pit, as illustrated in Figs. 11-16. Referring to Fig. 11, a substrate 110 is shown which includes an a diamond cross-sectional shaped etch-stop pit 116 with two V-grooves 114, 115 disposed on opposing sides of the etch-stop pit 116. The V-grooves 114, 115 have longitudinal axes are collinear and intercept at a respective vertex of the etch-stop pit 116. The region of intersection between each V-groove 114, 115 with the respective portion of the etch-stop pit 116, has a similar geometry to the intersection between the V-groove 14 and etch-stop pit 16 depicted in Fig. 2D. Thus, for the same reasons given above, no wedge-shaped end wall is formed in the V-grooves 114, 115 at the locations adjacent the etch-stop pit 116. To allow the end faces of respective fibers disposed in two V-grooves 164, 165 to be space more closely together, the etch-stop pit 166 may comprise a diamond-like shape that is compressed, as illustrated in Fig. 16.

In a similar manner, the etch-stop pit 136 may have a cross-sectional shape suited to having a single V-groove 134 on one side of the etch-stop pit 136 and having two or more V-grooves 135, 137, 139, disposed at an opposing side of the etch-stop pit 136. In addition, the etch-stop pit 136 may have a cross-sectional shape suited to preventing the formation of a wedge-shaped end wall in each V-groove 134, 135, 137, 139 at the respective positions where the V-grooves 134, 135, 137, 139 adjoin the etch-stop pit 136. A suitable shape for such an etch-stop pit 136 as depicted in Fig. 13. The etch-stop pit 136 provides two fiber stops 137 for a fiber disposed in the V-groove 134. Yet additional shapes of an etch-stop pit 126 may be provided for preventing the formation of wedge-shaped end walls in multiple V-grooves 124, 125, 126, 127, as illustrated in Fig. 12. Wedge-shaped end walls do not form for the reasons given above with regard to Figs. 4D and 7, for example.

Still further, two of the 'etch-stop pit with adjoining V-groove'-structures illustrated in Fig. 2D may be provided in a single substrate 140 in back-to-back coaxial relationship with a passageway 149 extending between the two triangular sections of the etch-stop pit 146, as illustrated in Fig. 14. Such a configuration provides a fiber stop 147 for each of the V-grooves 144, 145 so that the distance, D, between the ends of two fibers located within the V-grooves 144,145 may be precisely

specified. In addition, the passageway 159 may be sufficiently long so as to provide for insertion of an optical element between the two fiber stops 157. A slot 153, or other suitable shape, is provided to receive such an optical element.

In yet another aspect of the present invention, two or more the above-described 'etch-stop pit with adjoining V-groove' structures may be provided in a substrate with a V-pit disposed therebetween, as shown in Figs. 17, 18, and 20. A V-pit 179, 189, 209 may be formed by anisotropic etching by the same methods used to form V-grooves but using a square aperture mask rather than a rectangular aperture mask. The V-pit 179, 189, 209 may be anisotropically etched at the same time as the grooves 174, 184, 204. The V-pit 179, 189, 209 should be etched after the etch-stop pit 176, 186, 206 and the etch-stop layer are provided, in accordance with the process described above in reference to Fig. 2D. The V-pit 179, 189, 209 comprises for triangular-shaped, sidewalls that lie in the {111} crystallographic planes to form a four-sided regular pyramid that extends into the substrate 170, 180, 200. Like the V-grooves 174,184 the V-pits 179,189 should extend into the substrate a depth less than the depth of the etch-stop pits 176, 186 at the point of intersection between the V-pits 179, 189 and the etch-stop pits 176, 186, as illustrated in Fig. 17 and 18. In a configuration where the V-pit 209 does not intercept the etch-stop pit 206, the V-pit 209 depth does not need to be selected with regard to the depth of the etch-stop pit 206. The V-pits 179, 189, 209 provide a convenient shape for retaining a spherical optical element the V-pits 179, 189, 209, such as a ball lens. The V-grooves 174, 184, 204 are positioned so that an optical element disposed within the V-grooves 174, 184, 204 can optically communicate with the optical element disposed within the respective V-pit 176, 186, 206. In alternative configuration, as illustrated in Fig. 19, the etch-stop pit 196 may contain a central portion 195 configured to hold a spherical optical element. For example, the central portion may have a diamond-like shape. The central portion 195 of the etch-stop pit 196 may serve the same function of retaining a spherical optical element as that of the V-pit 189.

In another aspect of the present invention, an etch-stop pit may be provided at a location where two anisotropically etched features would intersect to form an inside, convex corner. A convex corner formed by the intersection of two {111} planes does not form a straight line intersection between two planes, but rather creates a rounded intersection between the two intersecting {111} planes. The rounding can propagate

to remove material in the vicinity of the intersection, such that the well-defined {111} planes can be etched away in the vicinity of the intersection to yield structures that are not {111} planes. Thus, it would be desirable to prevent the formation of such rounded corners.

Figs. 21-28 illustrate several configurations of etch-stop pits in accordance with the present invention which are suited to prevent undesirable etching at an inside, convex corner. Each of the structures in Figs. 21-28 may desirably be formed by the process described above with reference to Fig. 2D, with an etch-stop pit and etch-stop layer provided in the substrate prior to anisotropically etching the V-grooves. For example, referring to Fig. 21, a top elevational view of the substrate 210 is shown in which two V-grooves 214 are disposed. The two V-grooves 214 are oriented with their respective longitudinal axes at 90 degrees relative to one another. An etch-stop pit 216 is provided at a selected location of the substrate 210 corresponding to the location at which the two V-grooves 214 would otherwise intersect. Providing the etch-stop pit 216 at the selected location prevents intersection of the V-grooves 214. The etch-stop pit 216 may be disposed at a 45 degree angle, β, so that wedge-shaped end walls are not formed in the V-grooves 214 adjacent the etch-stop 216. To provide for greater ease of alignment (lower alignment tolerances) between the etch-stop pit 216 and the longitudinal axis of the V-grooves 214, an angle of less than 45 degrees may be preferable.

Alternative configurations of an etch-stop pit that prevent etching of an inside, convex corner and wedge-shaped V-groove end walls are illustrated in Figs. 22-28. Each configuration depicted in Figs. 22-28 includes V-grooves 224, 234, 244, 254, 264 oriented at 90 degrees with an intermediate etch-stop pit 226, 236, 246, 256, 266 in a similar configuration to that of Fig. 21. The etch-stop pit 226, 236, 246, 256, 266 is located to prevent intersection of the V-grooves 224, 234, 244, 254, 264. Each of the etch-stop pits 226, 236, 246, 256, 266 has straight wall segments disposed at an angle of 45 degrees or less with respect to the longitudinal axis of an adjacent V-groove 224, 234, 244, 254, 264. Referring to Figs. 22 and 23, the etch-stop pit 226, 236 may include an interior portion 225, 235 for retaining optical element such as filters, lenses, micromechanical switches, for example. In addition, as illustrated in Figs. 25 and 26, the etch-stop pit 256, 266 may have a shape configured to provide a fiber stop 257, 267 for fibers 251, 261 disposed within the V-grooves 254, 264.

In accordance with the present invention, yet additional configurations of etch-stop pits 276, 286 are provided which permit the intersection of two V-grooves 274, 284 while preventing the formation of an inside, convex corner 275, 285, thus obviating the need for corner compensation, as illustrated in Figs. 27 and 28. For example, a top elevational view of a substrate 270, 280 is shown in which pairs of V-grooves 274, 284 are provided in an upper surface of the substrate 270, 280. Pairs of V-grooves 274, 284 intersect at ends of the V-grooves 274, 284 at an angle of 90 degrees. An etch-stop pit 276, 286 is provided at a selected location of the substrate 270, 280 corresponding to the location at which an inside corner 275, 285 of the intersecting V-grooves 274, 284 would otherwise be formed. Providing the etch-stop pit 276, 286 coated with an etch-stop layer at the selected location prevents formation of the inside convex corner 275, 285.

In a further aspect of the present invention, an etch-stop pit 296 may be provided as a continuous boundary that circumscribes a region of the substrate 294 that is to be anisotropically etched. Providing such an etch-stop pit boundary permits the anisotropically etched features to be etched more deeply than otherwise possible. For example, referring to Fig. 30, a cross-sectional view of a substrate 300 is shown in which a recessed V-groove 304 is provided. The ability to form the V-groove 304 below the plane of the upper surface 301 is provided by the presence of the etch-stop pit 306 (coated with an etch-stop layer) which circumscribes the region in which the V-groove 304 is formed. If the etch-stop pit 306 were not provided, the surfaces of the V-groove 304 would extend upward to the upper surface 301 as indicated by the dashed line 307, and thus would not be recessed with respect to the upper surface 301.

Turning now to Figs. 29A-D, an L-shaped etch-stop pit 296 is provided which circumscribes an L-shaped area in which an anisotropically etched feature may be formed. Providing the L-shaped etch-stop pit 296 permits the formation of {111} sidewalls as illustrated in Figs. 29A and 29B. Etching for a longer period of time permits a deeper feature to be formed, as illustrated in Figs. 29C and 29D. Alternatively, other shapes than L-shaped may be utilized as an etch-stop pit. For example, the etch-stop pit 316 may have a T-shaped cross-section as illustrated in the top view of Fig. 31. Upon anisotropically etching the region 311 bounded by the T-shaped etch-stop pit 316, {111} sidewalls may be formed as illustrated in Figs. 32A and 32 B. In the vicinity of the cross-sectioning plane B – B, the anisotropically

etched feature 324 may have a V-shaped cross-section, as illustrated in Fig. 32B. Yet further shapes may be utilized in accordance with the present invention as an etch-stop pit which circumscribes an area to be anisotropically etched, such as the configuration depicted in Fig. 33.

In yet another aspect of the present invention, a U-shaped etch-stop pit 346 is provided adjacent to a V-pit 345 to provide a location on a substrate 340 for mounting an optical element, such as a laser mount 355, and to provide a location for retaining an optical element, such as a spherical optical element 350, as illustrated in Figs. 34-36. Figs. 34 and 35A illustrate a top view of a substrate 340 in which a U-shaped etch-stop pit 346 is provided adjacent a V-pit 345. The U-shaped etch-stop pit 346 includes sidewalls that extend a selected depth into the substrate 340. Optionally, the sidewalls of the U-shaped etch-stop pit 346 may be vertical, as illustrated in Fig. 34. Alternatively, the sidewalls of the U-shaped etch-stop pit 346 may be inclined relative to the upper surface 301 of the substrate 340. The sidewalls of the U-shaped etch-stop pit 346 are conformally coated with an etch-stop layer, or, optionally, the etch-stop pit 346 is filled etch-stop layer material. In addition, the portion 343 of the substrate surface 301 interior to the etch-stop pit 346 may be provided with an etch-stop layer. As explained above with reference to the process of Figs. 2A-2D, the etch-stop layer comprises a material that is resistant to the etching used to form an anisotropically etched feature, such as V-pit 345.

After the desired etch-stop layer or layers are provided, the V-pit 345 may be formed by anisotropic etching by the same methods used to form V-grooves but using a square aperture mask. Instead of using a perfectly square aperture mask, a generally square-aperture that includes a protrusion to protect substrate surface portions 343 interior to the etch-stop pit 346 may be used. The V-pit 345 may be anisotropically etched at the same time as the optional V-groove 354. The V-pit 345 should extend into the substrate a depth less than the depth of the etch-stop pit 346 at the point of intersection 353 between the V-pit 345 and the etch-stop pit 346, as illustrated in Fig. 35B. In a configuration where the V-pit 345 does not intercept the etch-stop pit 346, the V-pit 345 depth does not need to be selected with regard to the depth of the etch-stop pit 346.

The V-pit 345 provides a convenient shape for retaining a spherical optical element, such as a ball lens 350. The interior portion 343 of the substrate surface 301

provides a convenient location at which a laser 355, or other optical device, may be located for optical communication with the ball lens 350. Providing the U-shaped etch-stop pit 346 permits a portion of the V-pit 345 adjacent the etch-stop the 346 to be recessed below the surface 341 of the substrate 340. Such a recess permits the ball lens 350 to be positioned more closely to the laser 355, as illustrated in Fig. 35B. In addition, a V-groove 354, 374 may also be provided for optical communication between a fiber disposed with the V-groove 354, 374 and the V-pit, as illustrated in Figs. 36 and 37. With respect to Fig. 36, the V-groove 354 may be fabricated in a similar manner as the V-grooves 174 of Fig. 17, for example. Alternatively, as illustrated in Fig. 37, the etch-stop pit 376 may circumscribe the region in which the V-pit 375 is formed. The etch-stop pit 376 comprises a U-shaped segment 366 to provide an analogous function to that of the U-shaped etched pit 346 in the configuration of Fig. 35A. The etch-stop pit 376 also comprises a triangular-shaped segment 378 to prevent formation of a wedge-shaped end wall in the V-groove 374 and to provide a fiber stop 377.

Methods of Fabrication

In accordance with the present invention, there are provided methods for fabricating optical subassemblies having an etch-stop pit and an adjacent recessed area, such as an anisotropically etched area, for receiving an optical element. Three exemplary methods are illustrated in the flowcharts of Figs. 40-42 and the accompanying side cross-sectional views of Figs. 45-64. The orientation of the side cross-sectional views of Figs. 45-64 is illustrated in Figs. 43 and 44.

Referring to Fig. 43, a top elevational view is shown of a substrate 440 in which a V-groove 444 and adjacent etch-stop pit 446 are provided. The structure shown in Fig. 43 is similar to that shown in Fig. 2D, where one of the wedge-shaped end walls is eliminated from the V-groove 444. A cross-sectional view taken along the line B – B is illustrated in Fig. 44 to show a cross-section of the V-groove 444 at a location where the V-groove 444 intersects the etch-stop pit 446. Figs. 45-64 illustrate cross-sectional views of substrates which are taken along the same view direction, B – B, as the cross-sectional view in Fig. 44. The exemplary part fabricated by each of the methods illustrated in the flowcharts of Figs. 40-42 has a final configuration similar to that of the device shown in Figs. 43 and 44.

Referring now to Fig. 40, there is shown a flowchart illustrating a method in accordance with the present invention for creating the device illustrated in Figs. 43 and 44. As illustrated in Fig. 45, a substrate 450 made from <100>-oriented Si is provided. The processing of the substrate 450 begins at step 4000 of Fig. 40 by providing a protective layer 452 on a first surface of the substrate 450 to cover that portion of the substrate 450 in which the etch-stop pit 516 is not to be provided. That is, the protective layer 452 includes an etch-stop pit aperture 451 through which a portion of the substrate 450 surface is accessible for forming the etch-stop pit 516.

The protective layer 452 may be deposited over the entire surface of the substrate 450. Thereafter, portions of the protective layer 452 may be removed to expose the surface of the substrate 450 at the selected area for the etch-stop pit 516. The material of the protective layer 452 is chosen to be resistant to the etchant that will be used to form the V-groove 512. For example, silicon dioxide is one suitable material. The silicon dioxide may be deposited by CVD or may be provided by thermal oxidation of the substrate surface. The silicon dioxide layer should be thick enough to serve as a mask during the etch-stop pit formation.

Following the application of the protective layer 452, an aperture definition layer 454 is deposited, at step 4010, over a selected portion of the protective layer 452, as shown in Fig. 45. The aperture definition layer 454 is provided so that an aperture 457 may be provided, as explained below, through which the V-groove 512 will be etched. The location of the aperture definition layer 454 is selected to cover that portion of the substrate surface at which the V-groove 512 is to be located.

Processing continues with the selective removal, at step 4020, of a portion of the substrate 450 located within the etch-stop pit aperture 451 to form an etch-stop pit 516 in the substrate 450, as depicted in Fig. 46. The etch-stop pit 516 may conveniently be formed by reactive ion etching, plasma etching, ion milling, or by any other directional process. In addition, the etch-stop pit 516 may be formed by other methods such as isotropic or anisotropic etching, so long as the etch-stop pit 516 attains the desired shape and depth.

Having created the etch-stop pit 516, the surfaces of the etch-stop pit 516 are covered, preferably conformally, with an etch-stop layer 458, at step 4030, as illustrated in Fig. 47. The etch-stop layer 458 may be conveniently provided by thermally oxidizing the substrate to provide an etch-stop layer 458 comprising silicon

dioxide. An appropriate choice for the etch-stop layer 458 includes any material that is resistant to the etchant which will be used to create the V-groove 512. During the thermal oxidation step 4030, the previously deposited silicon dioxide protective layer 452 increases in thickness and surrounds the perimeter of the aperture definition layer 454, as illustrated in Fig. 47.

With the etch-stop layer 458 in place, processing continues by removing, at step 4040, the aperture definition layer 454 to provide a V-groove aperture 455 in the protective layer 452, as shown in Fig. 48. A sufficient thickness of the protective layer 452 is removed, at step 4050, to expose the surface of the substrate 450 disposed below the aperture definition layer 454 so that the V-groove aperture 455 communicates with the surface of the substrate 450. A portion of the protective layer 452 and the etch-stop layer 458 remain on the surfaces where the V-groove 512 will not be formed, as illustrated in Fig. 49. A suitable process for removing a thickness of the protective layer 452 is a short duration, wet or dry, oxide etch.

Next, as shown in Fig. 50, the portion substrate 450 accessible through the V-groove aperture 455 is selectively removed, at step 4060, to form the V-groove 512, as illustrated in Fig. 50. Appropriate processes for the formation of the V-groove 512 include anisotropic etching with EDP or TMAH. KOH may also be used; however, since KOH can attack the protective layer 452 and etch-stop layer 458, KOH should only be used if the protective layer 452 and etch-stop layer 458 are sufficiently thick so as not to be completely removed by the KOH. As a final optional step, the remaining portions of the protective layer 452 and etch-stop layer 458 may be removed at step 4070, to yield the device illustrated in Fig. 51.

Referring now to Figs. 41 and 52-58, another method in accordance with the present invention is illustrated for creating the device shown in Figs. 43 and 44. As illustrated in Fig. 52, a substrate 520 made from <100>-oriented Si is provided. The processing of the substrate 520 begins at step 4100 of Fig. 41 by providing a first protective layer 522 on a first surface of the substrate 520 to cover that portion of the substrate 520 in which neither the etch-stop pit 586 nor the V-groove 582 is to be provided.

The first protective layer 522 may be deposited over the entire surface of the substrate 520. Thereafter, portions of the first protective layer 522 may be removed to expose the surface of the substrate 520 at the selected areas for the etch-stop pit 586

and the V-groove 582. The material of the first protective layer 522 is chosen to be resistant to the etchant that will be used to form the V-groove 582. For example, silicon nitride is one suitable material. The silicon nitride may be deposited by CVD.

Following the application of the first protective layer 522, a second protection layer 524 is deposited, at step 4110, over a selected portion of the first protective layer 522 and the substrate surface where the V-groove 582 is to be formed, as shown in Fig. 52. The second protection layer 524 includes an aperture 521 through which the etch-stop pit 586 may be formed.

Processing continues with the selective removal, at step 4120, of a portion of the substrate 520 located within the etch-stop pit aperture 521 to form an etch-stop pit 586 in the substrate 520, as depicted in Fig. 53. The etch-stop pit 586 may conveniently be formed by reactive ion etching, plasma etching, ion milling, or by any other directional process. In addition, the etch-stop pit 586 may be formed by other methods such as isotropic or anisotropic etching, so long as the etch-stop pit 586 attains the desired shape and depth.

Having created the etch-stop pit 586, the surfaces of the etch-stop pit 586 and second protective layer 524 are covered, preferably conformally, with an etch-stop layer 528, at step 4130, as illustrated in Fig. 54. The etch-stop layer 528 may be conveniently provided by CVD. An appropriate choice for the etch-stop layer 528 includes any material that is resistant to the etchant which will be used to create the V-groove 582, such as silicon nitride.

With the etch-stop layer 528 in place, processing continues by removing, at step 4140, the portion of the etch-stop layer 528 disposed on the upper surface 541 of second protective layer 524. The portion of the etch-stop layer 528 disposed within the etch-stop pit 586 is retained, as illustrated in Fig. 55. The removal step 4140 may be performed by any suitable method such as planarization or polishing. Subsequently, at step 4150, a second protective layer 524 is removed, as shown in Fig. 56, to provide a V-groove aperture 525. A suitable method for removing the second protective layer 524 includes etching with dilute HF.

Next, as shown in Fig. 57, the portion substrate 520 accessible through the V-groove aperture 525 is selectively removed, at step 4160, to form the V-groove 582, as illustrated in Fig. 50. Appropriate processes for the formation of the V-groove 582 include anisotropic etching with KOH. As a final optional step, the remaining

portions of the first protective layer 522 and etch-stop layer 528 may be removed at step 4170, to yield the device illustrated in Fig. 58.

Referring now to Figs. 42 and 59-64, yet another method in accordance with the present invention is illustrated for creating the device shown in Figs. 43 and 44. As illustrated in Fig. 59, a substrate 590 made from <100>-oriented Si is provided. The processing of the substrate 590 begins at step 4200 of Fig. 42 by providing protective an aperture definition layer 594 deposited over a selected portion of the substrate 590, as shown in Fig. 59. The location of the aperture definition layer 594 is selected to cover that portion of the substrate surface at which the V-groove 632 is to be located. A suitable material for use as the aperture definition layer 524 is silicon nitride.

The processing of the substrate 590 continues, at step 4210, by providing a photoresist layer 592 over the aperture definition layer 594 and over the portions of the substrate 590 not covered by the aperture definition layer 524. Photoresist layer 592 is patterned, using methods known in the art, to provide an etch-stop pit aperture 591, as illustrated in Fig. 59. Processing continues with the selective removal, at step 4220, of a portion of the substrate 590 located within the etch-stop pit aperture 591 to form an etch-stop pit 636 in the substrate 590, as depicted in Fig. 60. The etch-stop pit 636 may conveniently be formed by a process which does not remove the aperture definition layer 594. In addition, the etch-stop pit 636 may be formed by other methods such as isotropic or anisotropic etching, so long as the etch-stop pit 636 attains the desired shape and depth.

Having created the etch-stop pit 636, the photoresist layer 592 is removed, at step 4230. The surfaces of the etch-stop pit 636 and exposed surfaces of the substrate 590 are oxidized to form an etch-stop layer 598, at step 4230, as illustrated in Fig. 61. With the etch-stop layer 598 in place, processing continues by removing, at step 4240, the aperture definition layer 594 to provide an un-oxidized region 597 of the substrate 590, as shown in Fig. 62.

Next, as shown in Fig. 63, the un-oxidized region 597 of the substrate 590 is selectively removed, at step 4250, to form the V-groove 632, as illustrated in Fig. 63. Appropriate processes for the formation of the V-groove 632 include anisotropic etching with EDP or TMAH. KOH may also be used; however, since KOH can attack oxide etch-stop layer 598, KOH should only be used if the etch-stop layer 598 is

sufficiently thick so as not to be completely removed by the KOH. As a final optional step, the remaining portions of the etch-stop layer 598 may be removed at step 4260, to yield the device illustrated in Fig. 64.

These and other advantages of the present invention will be apparent to those skilled in the art from the foregoing specification. Accordingly, it will be recognized by those skilled in the art that changes or modifications may be made to the above-described embodiments without departing from the broad inventive concepts of the invention. For example, a non-anisotropically etched feature may be formed adjacent an etch-stop pit. It should therefore be understood that this invention is not limited to the particular embodiments described herein, but is intended to include all changes and modifications that are within the scope and spirit of the invention as set forth in the claims.

Claims

What is claimed is:

1. An optical microbench, comprising substrate having an etch-stop pit and an anisotropically etched feature disposed adjacent the etch-stop pit.

2. The optical microbench according to claim 1, wherein the anisotropically etched feature comprises a V-groove.

3. A method for micromachining a substrate comprising the step of forming an etch-stop pit and the step of forming an anisotropically etched feature adjacent the etch-stop pit.

4. The method according to claim 3 comprising coating the surfaces of the etch-stop pit with an etch-stop layer.

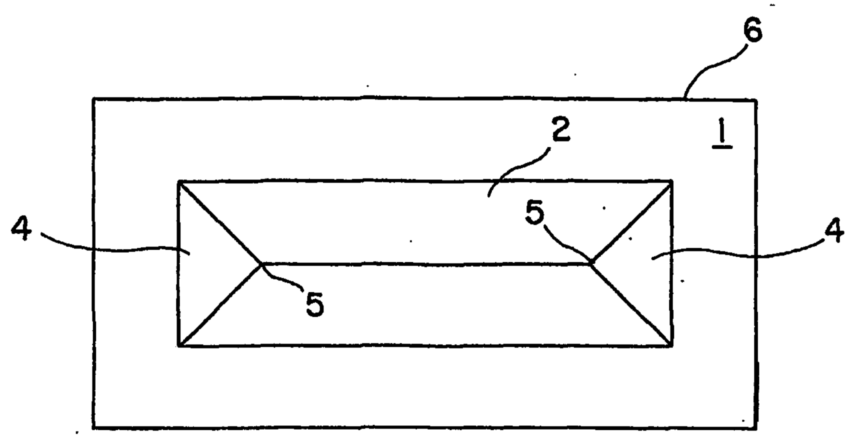

FIG. 1

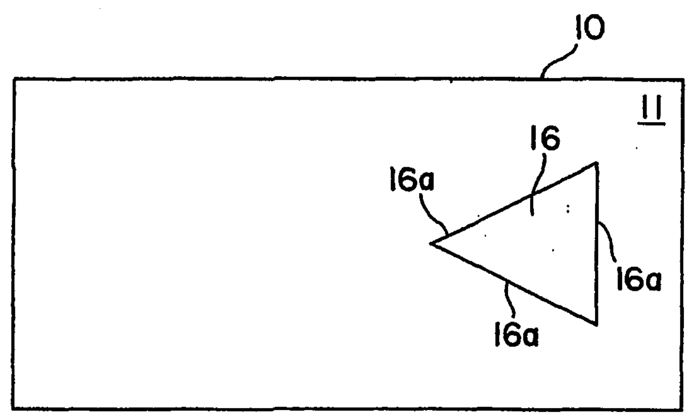

FIG. 2A

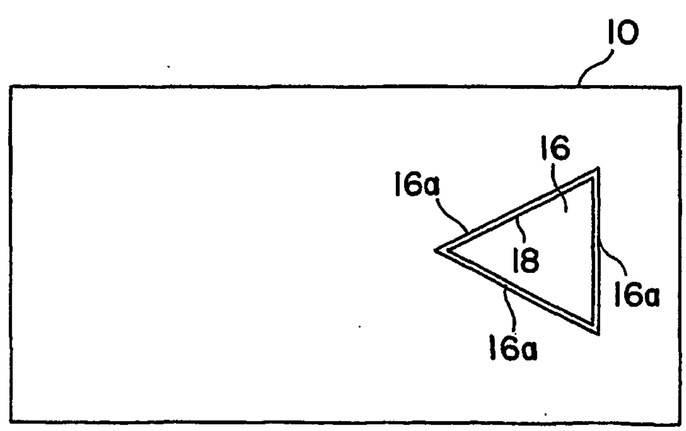

FIG. 2B

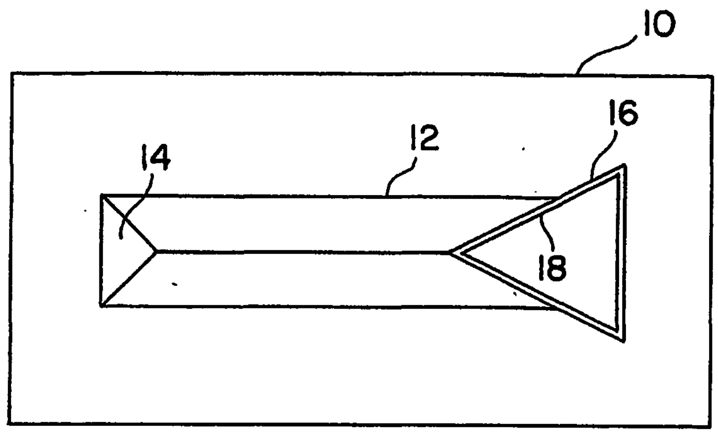

FIG. 2C

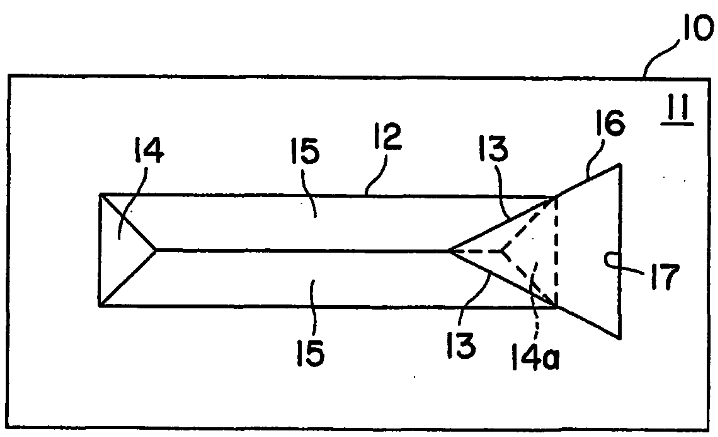

FIG. 2D

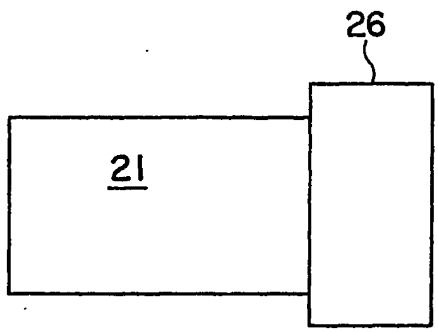

FIG. 3A

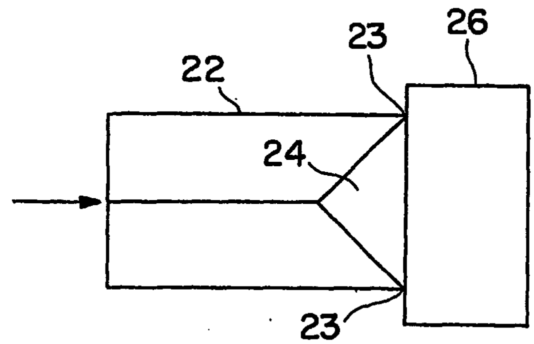

FIG. 3B

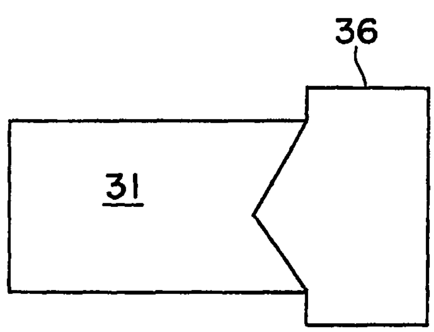

FIG. 3C

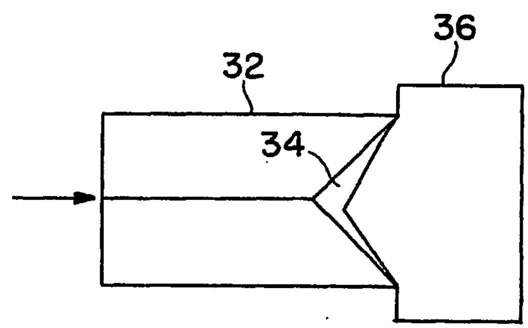

FIG. 3D

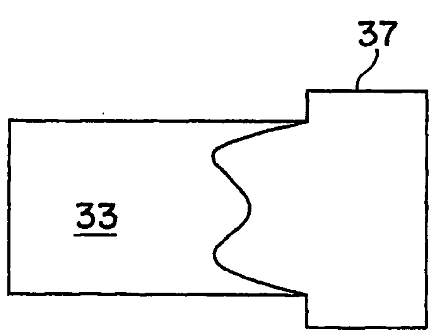

FIG. 3E

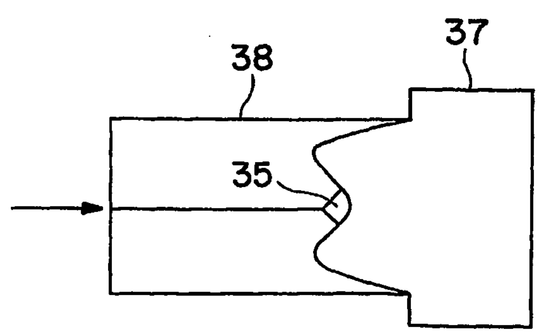

FIG. 3F

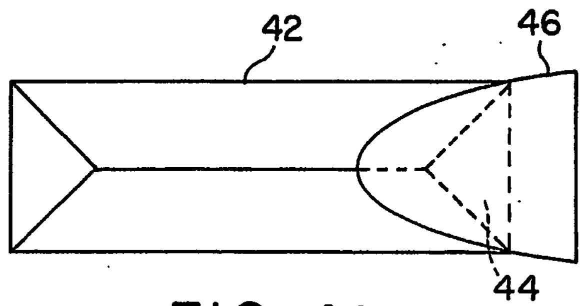

FIG. 4A

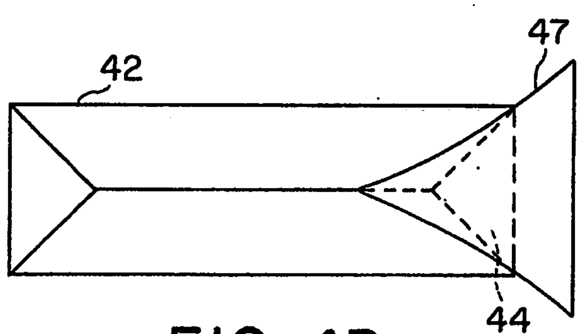

FIG. 4B

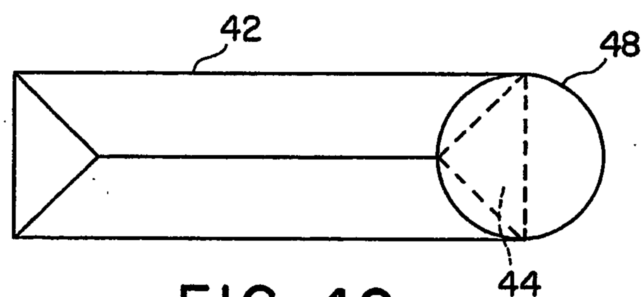

FIG. 4C

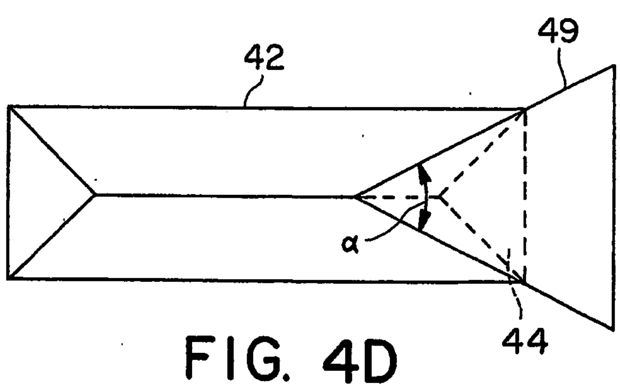

FIG. 4D

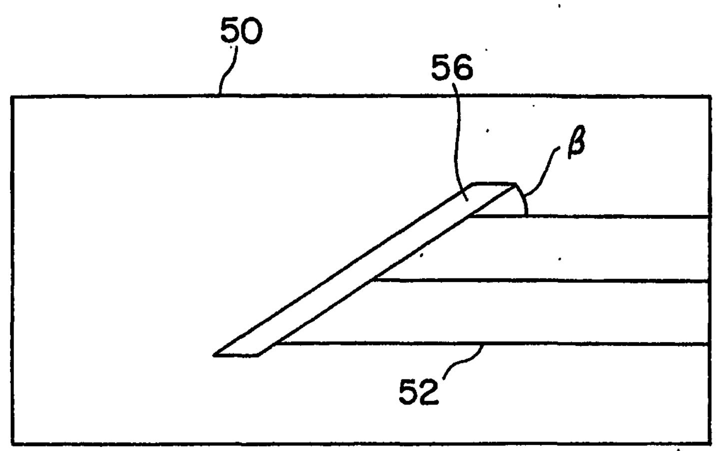

FIG. 5

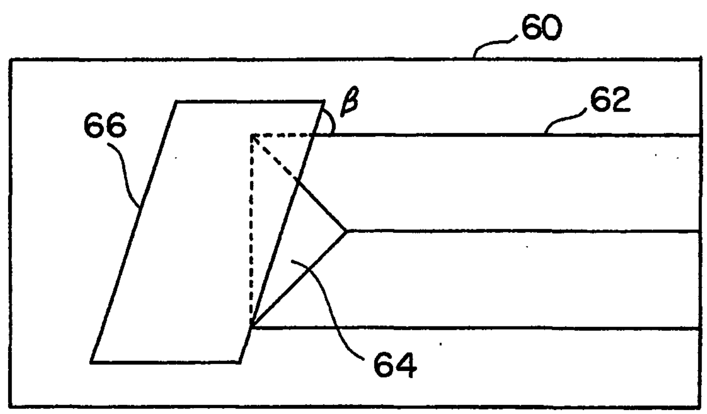

FIG. 6

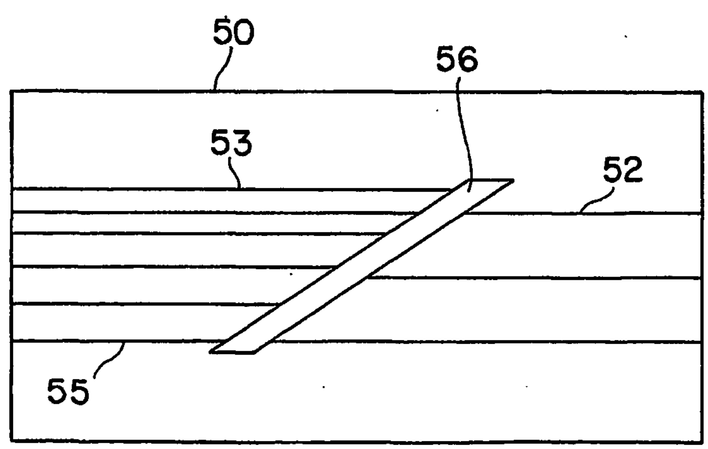

FIG. 7

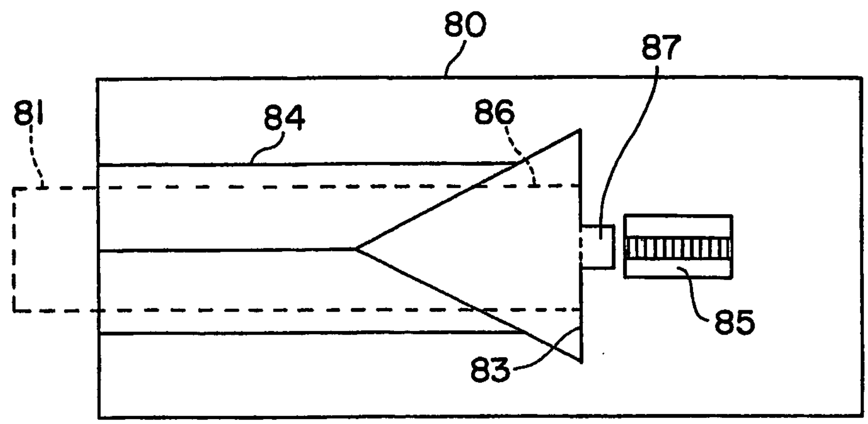

FIG. 8

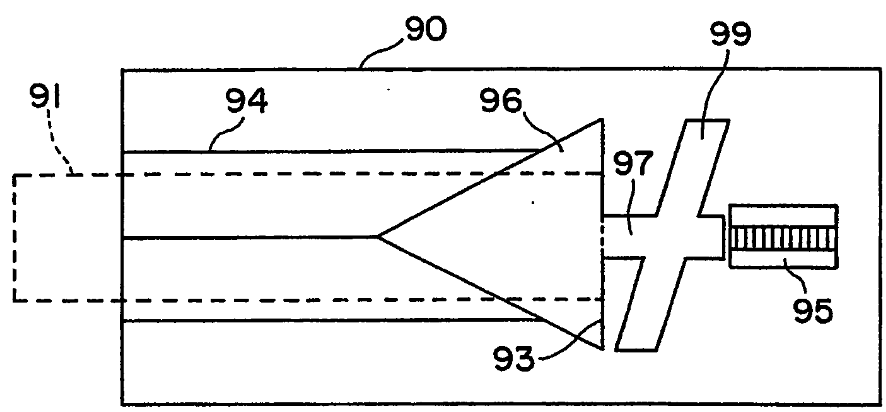

FIG. 9

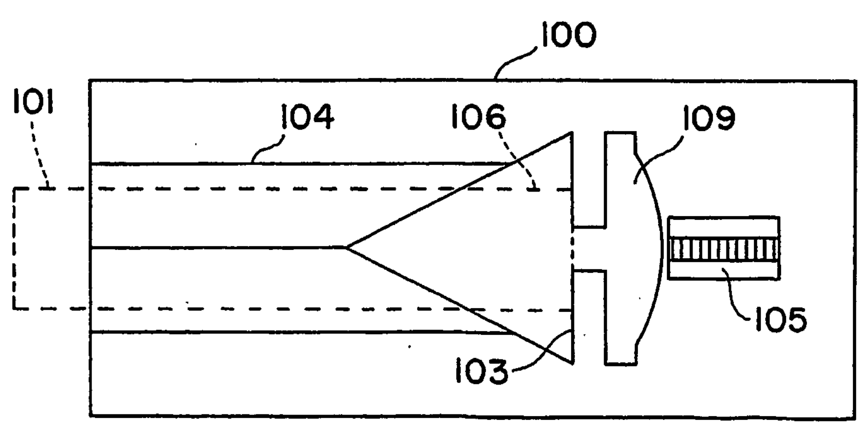

FIG. 10

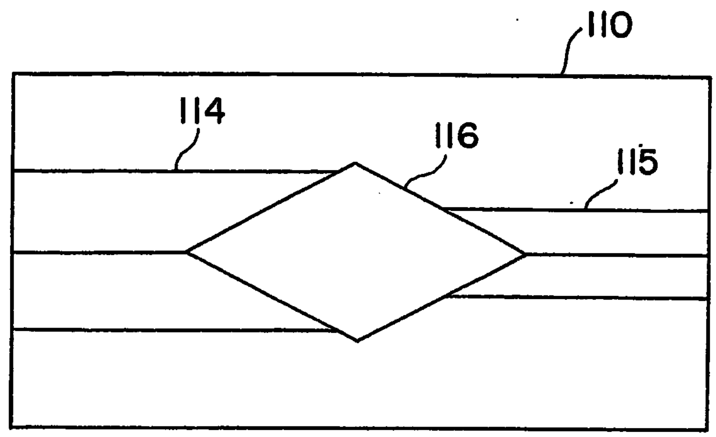

FIG. 11

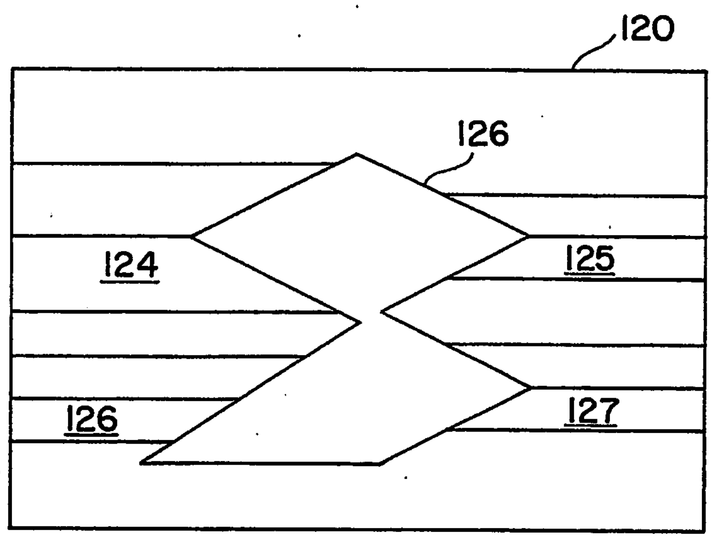

FIG. 12

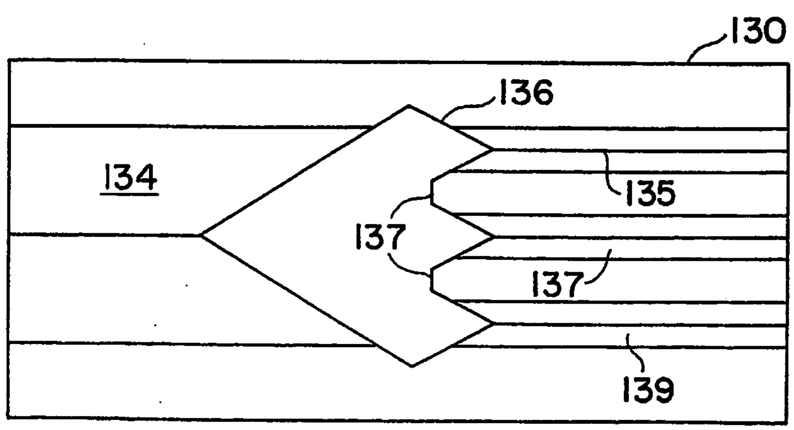

FIG. 13

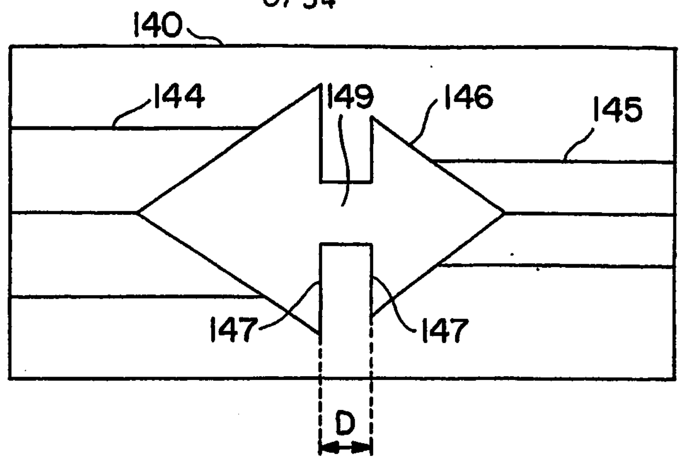

FIG. 14

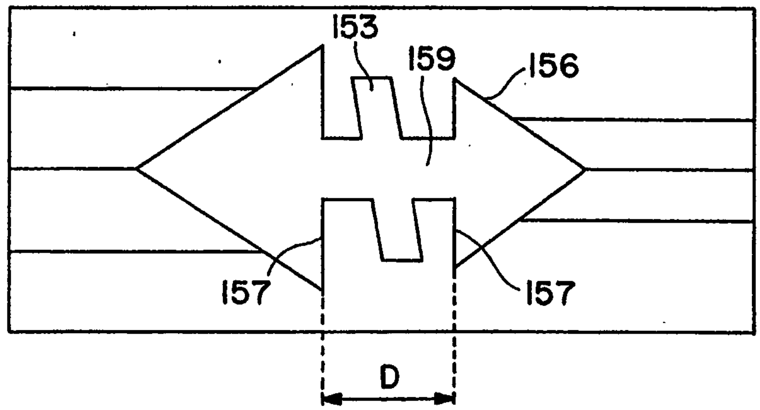

FIG. 15

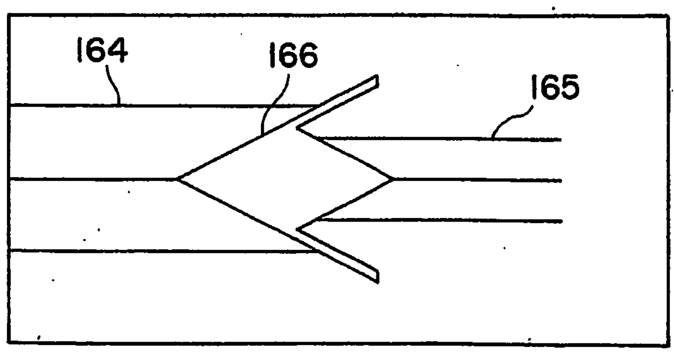

FIG. 16

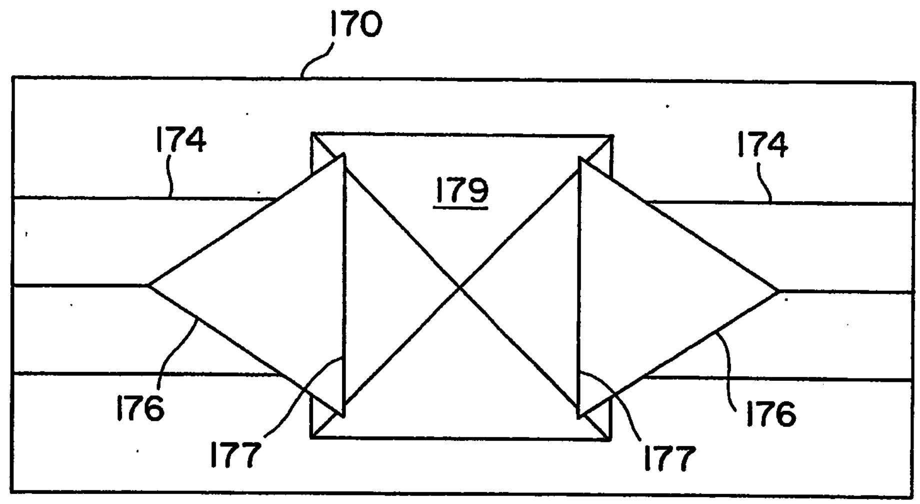
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FIG. 17

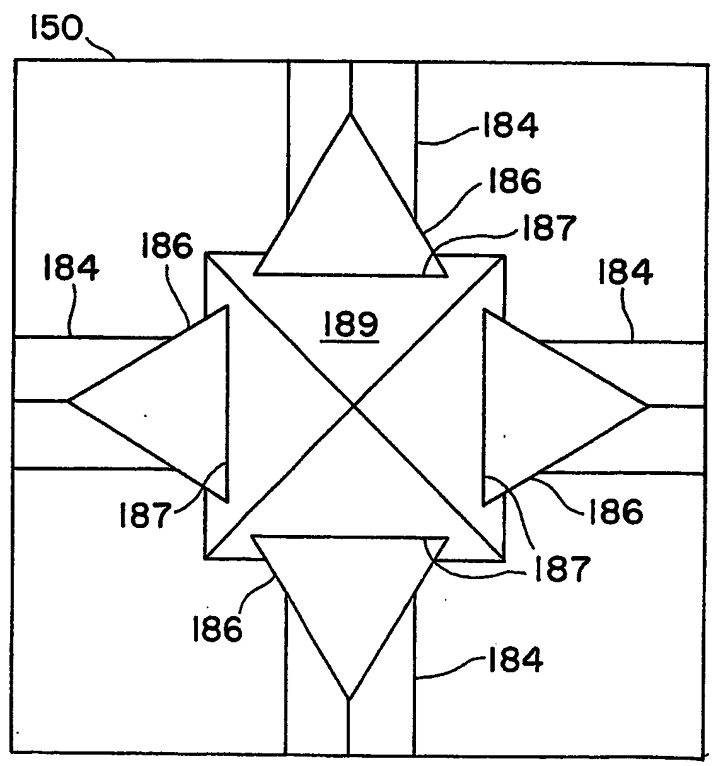
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FIG. 18

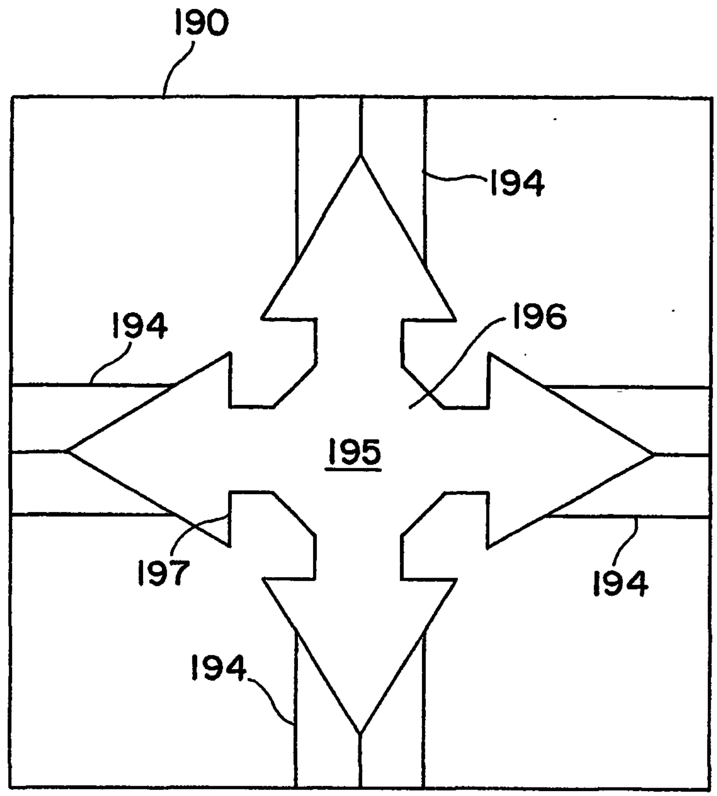

FIG. 19

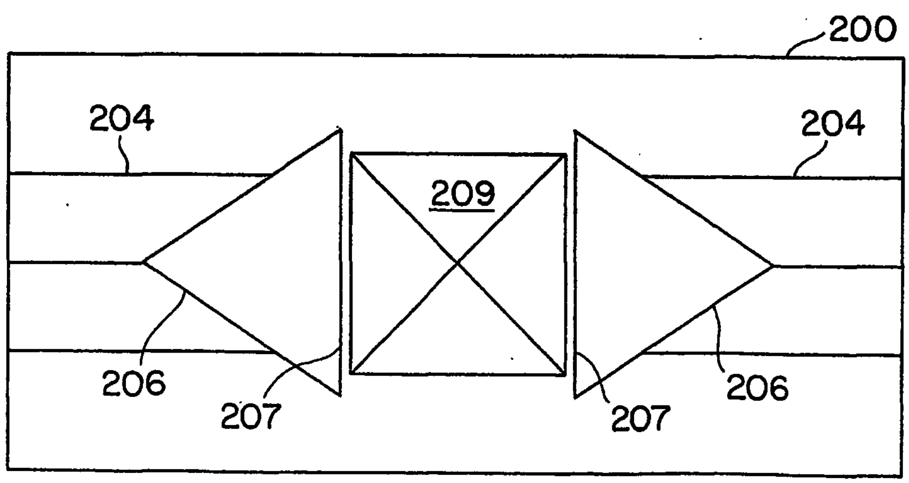

FIG. 20

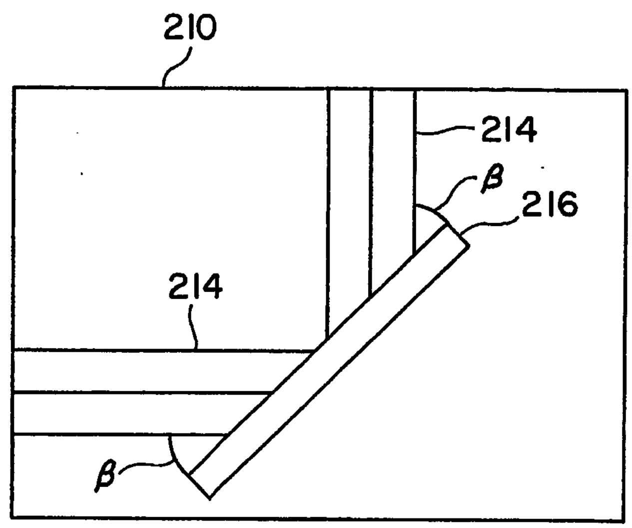

FIG. 21

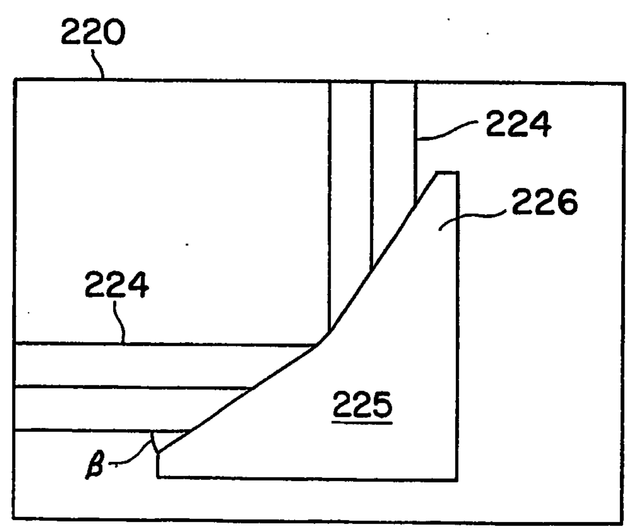

FIG. 22

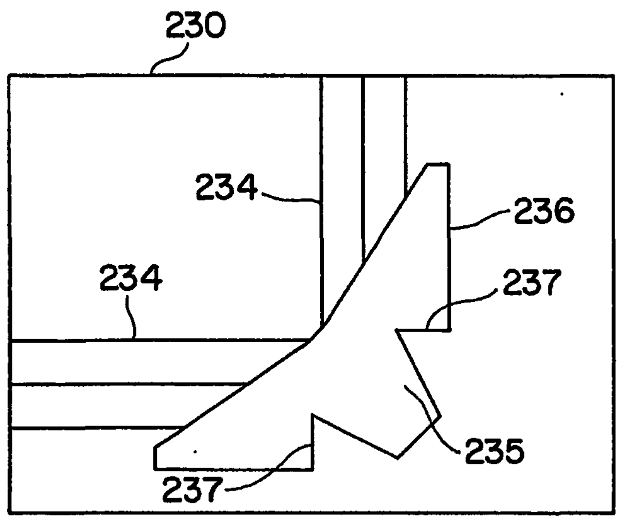

FIG. 23

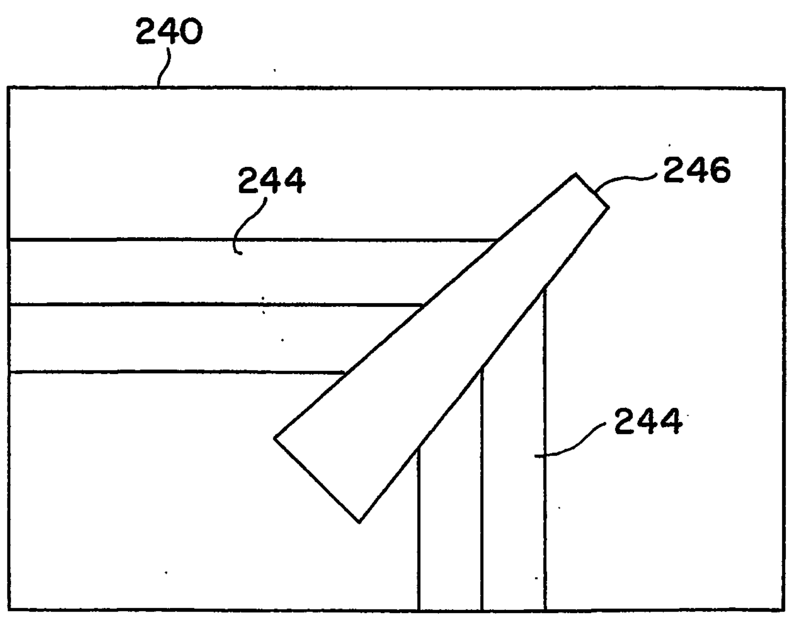

FIG. 24

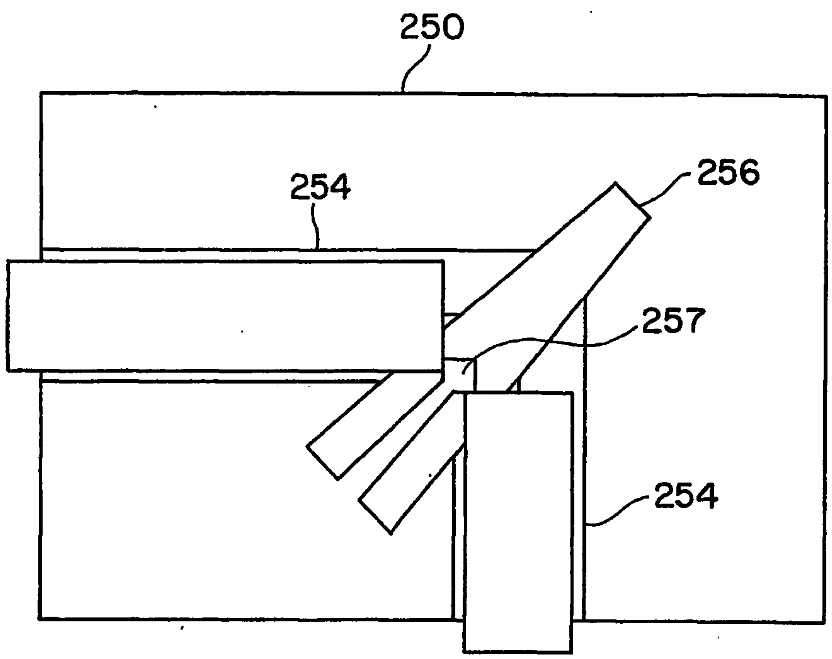

FIG. 25

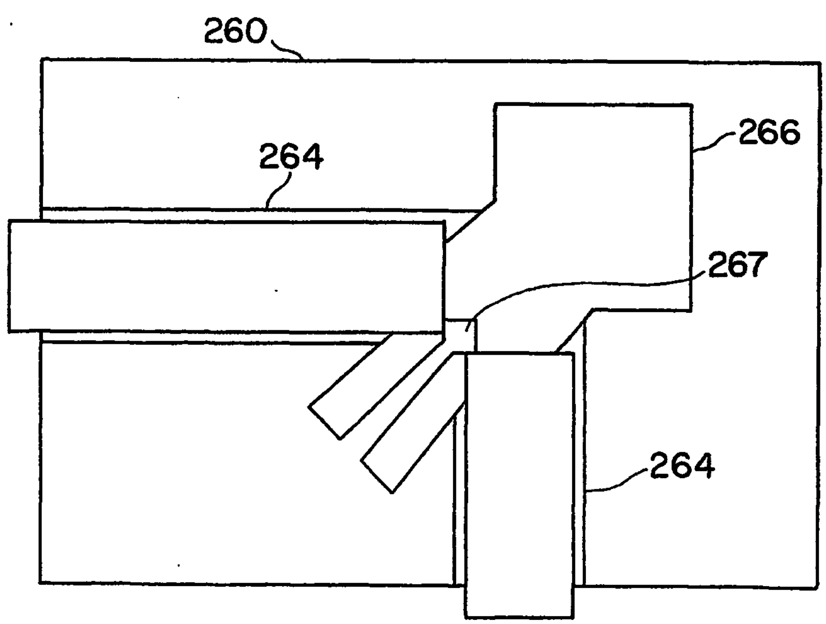

FIG. 26

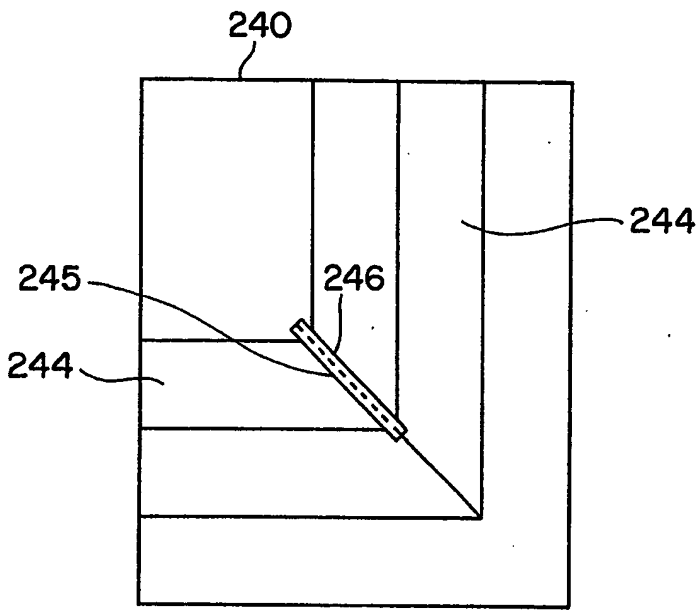

FIG. 27

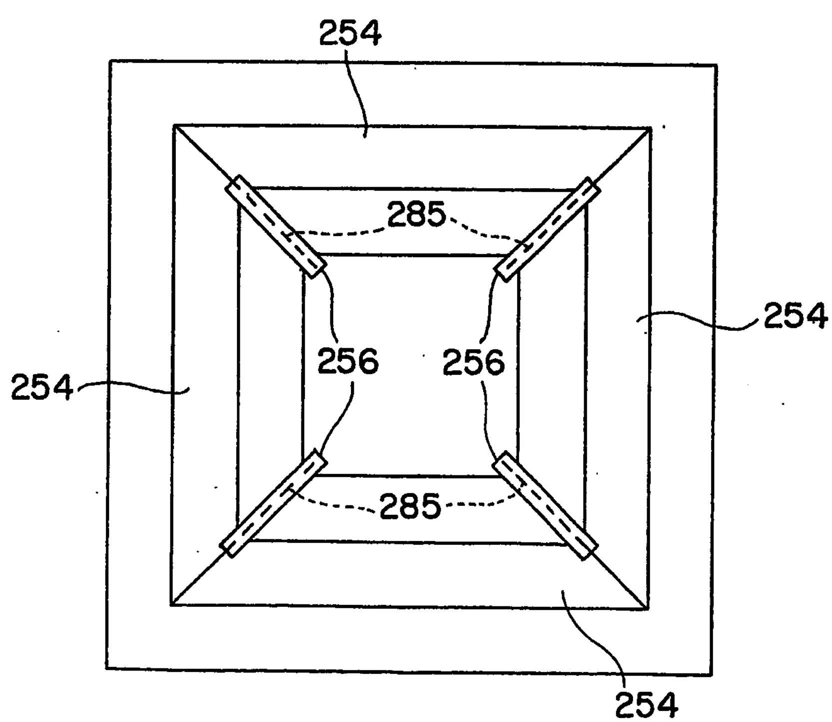

FIG. 28

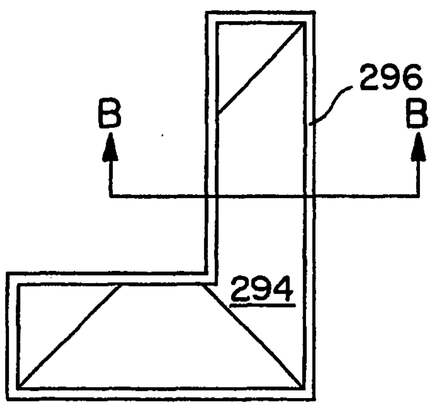

FIG. 29A

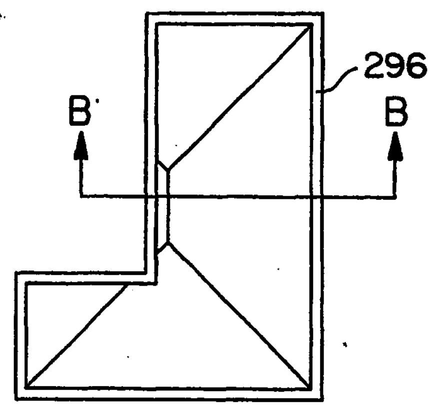

FIG. 29C

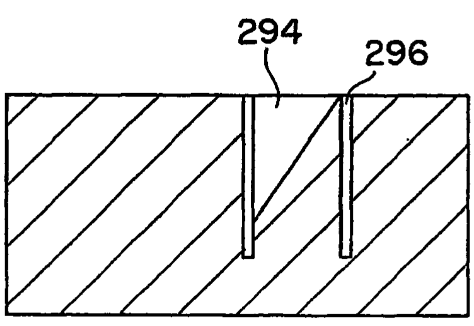

FIG. 29B

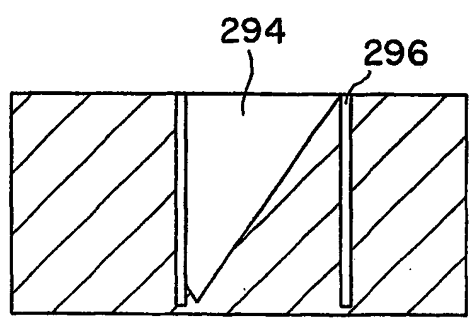

FIG. 29D

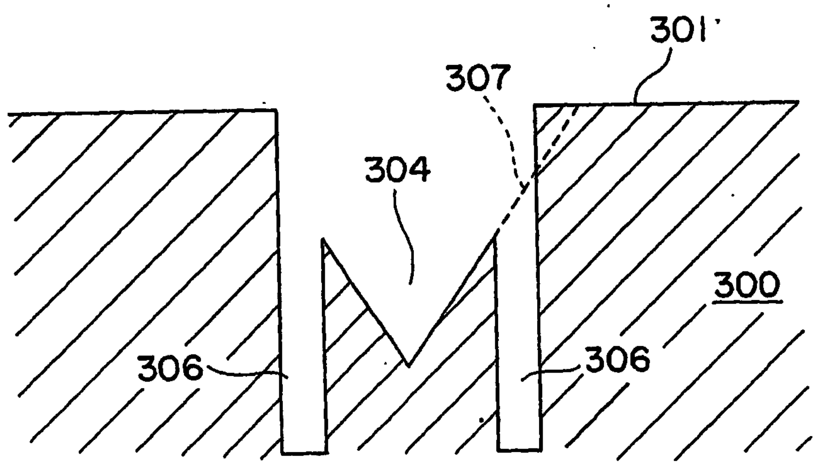

FIG. 30

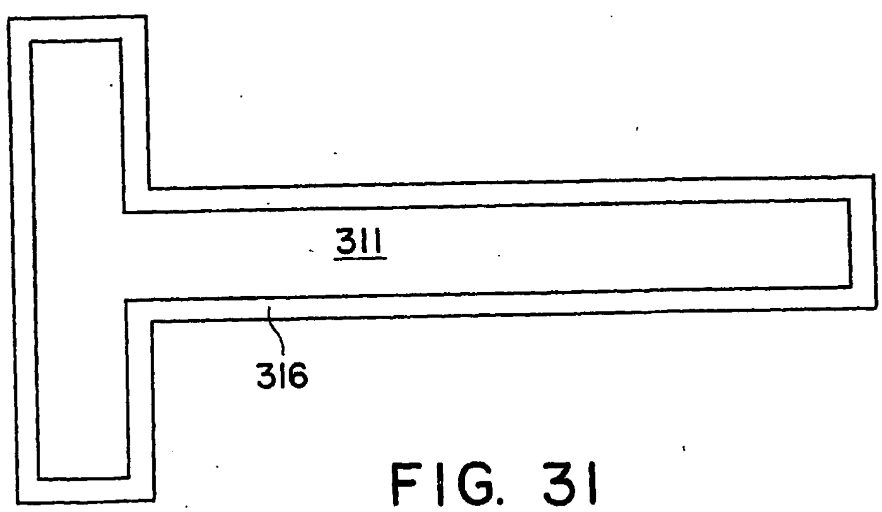

FIG. 31

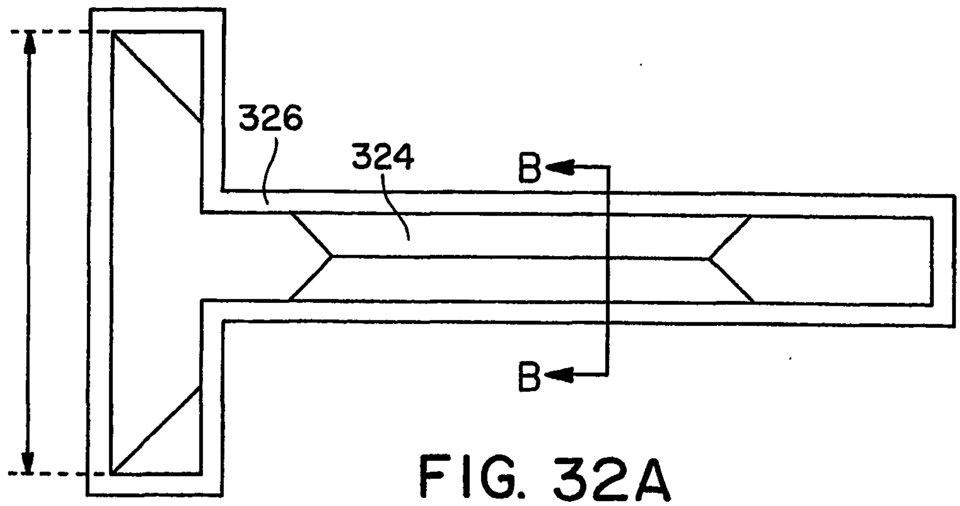

FIG. 32A

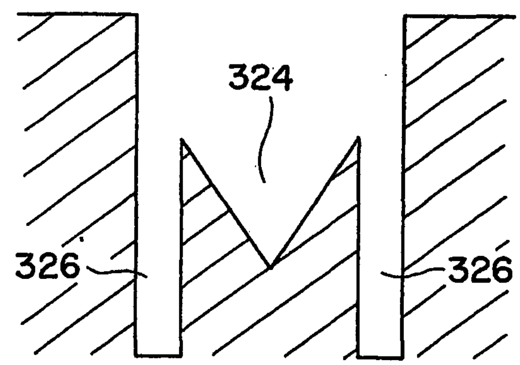

FIG. 32B

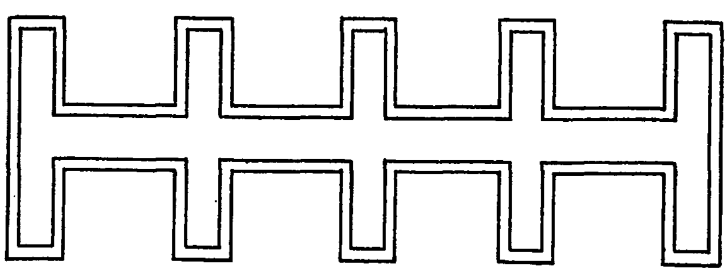

FIG. 33

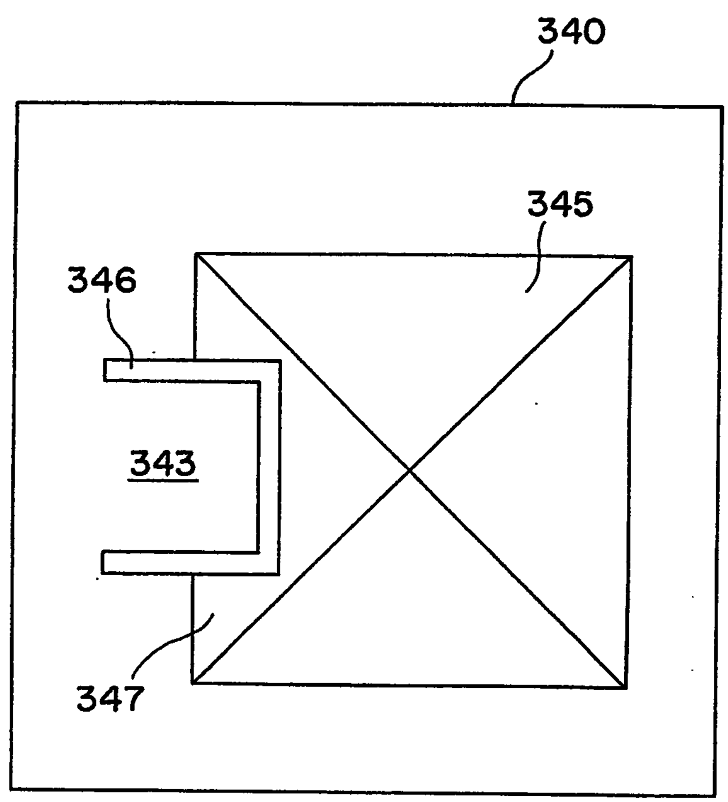

FIG. 34

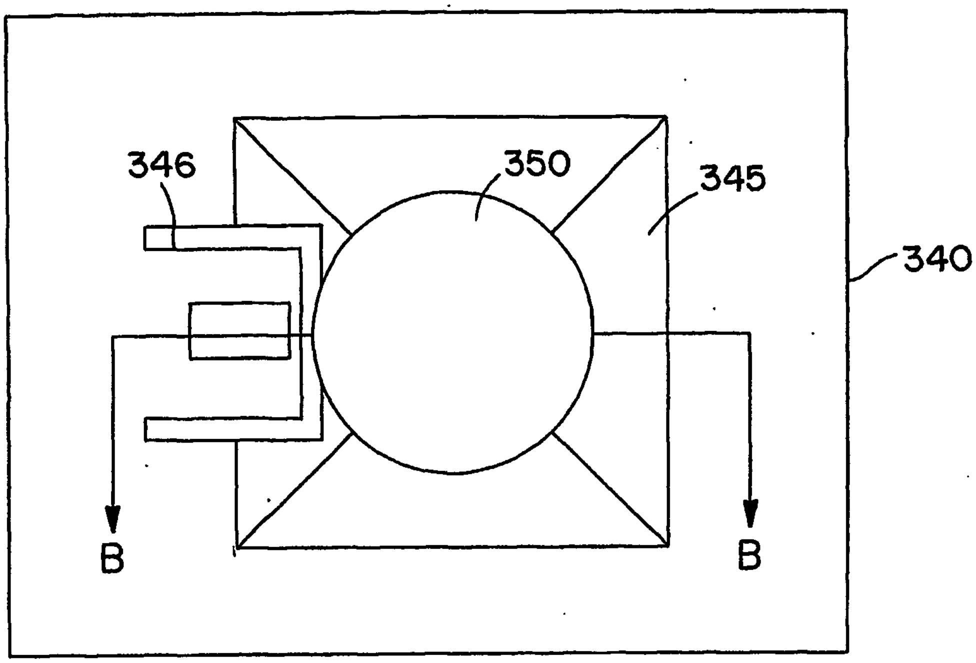

FIG. 35A

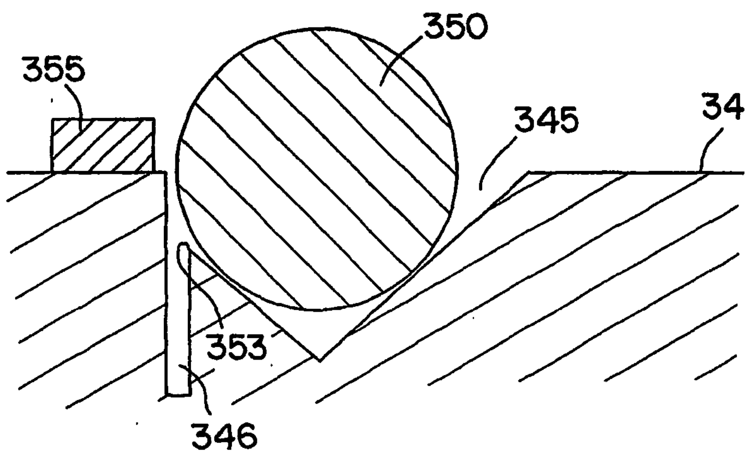

FIG. 35B

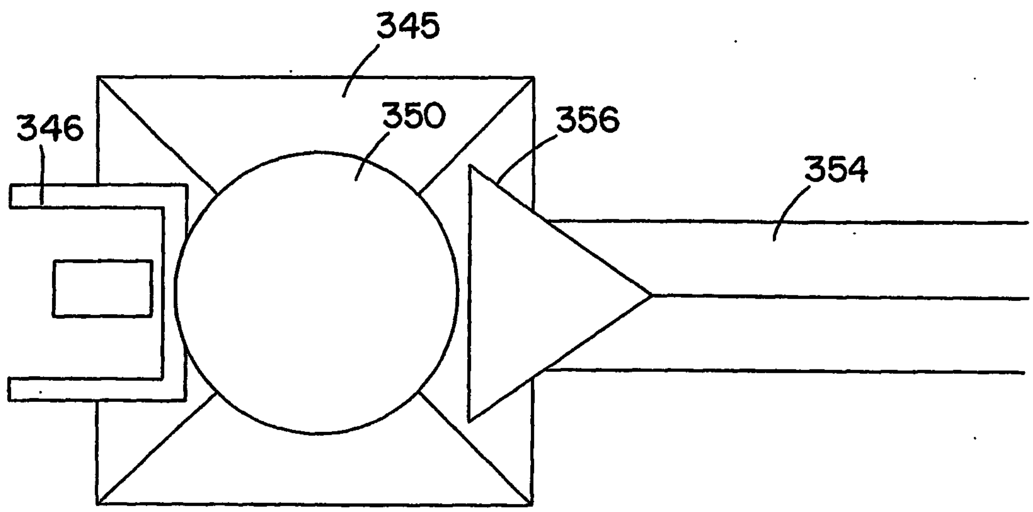

FIG. 36

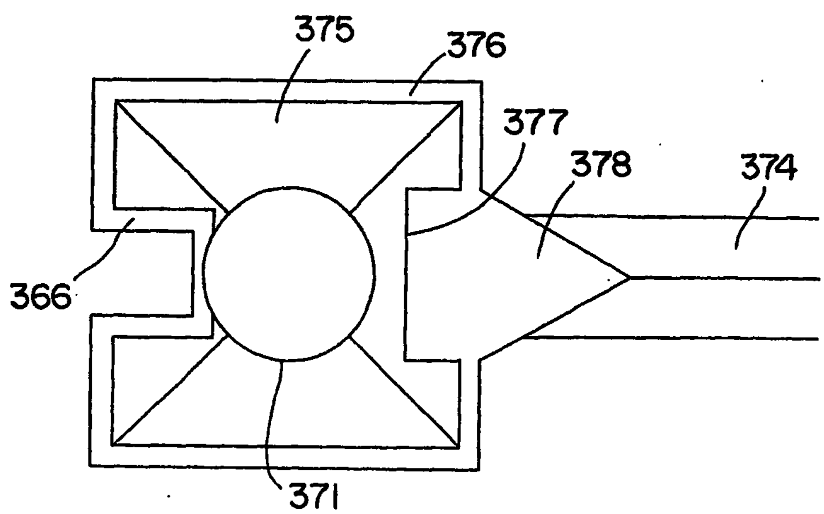

FIG. 37

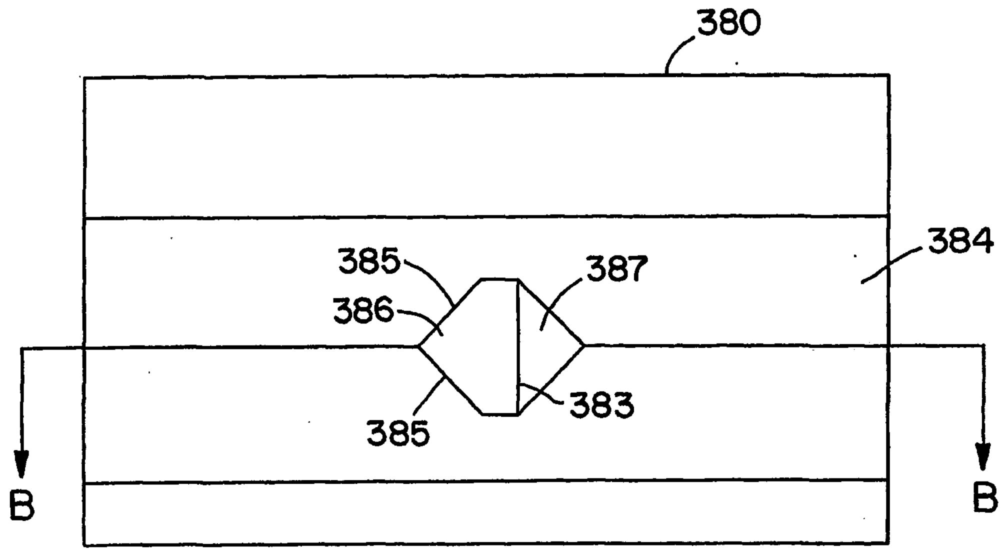

FIG. 38A

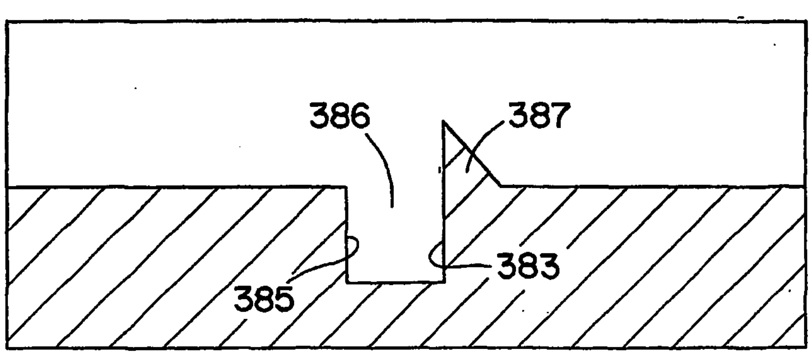

FIG. 38B

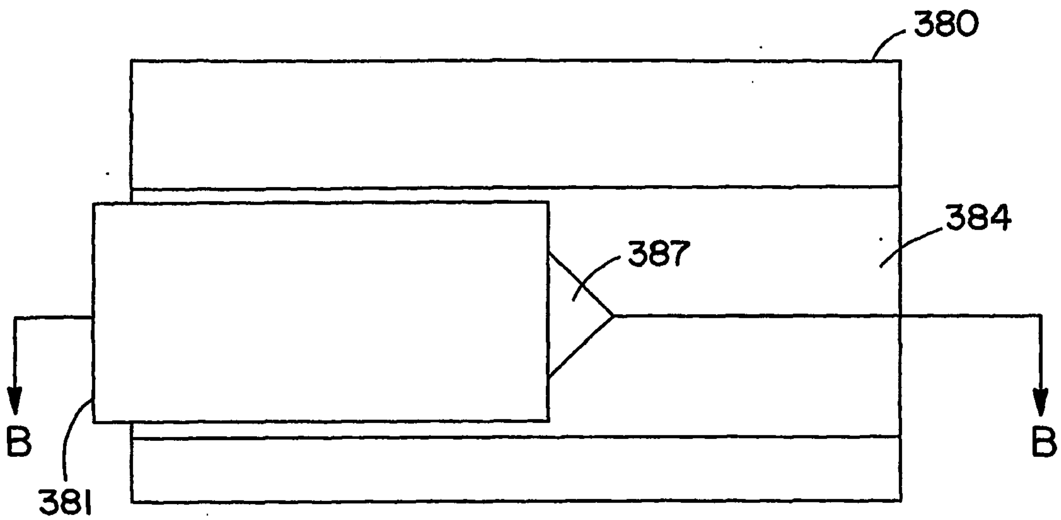

FIG. 39A

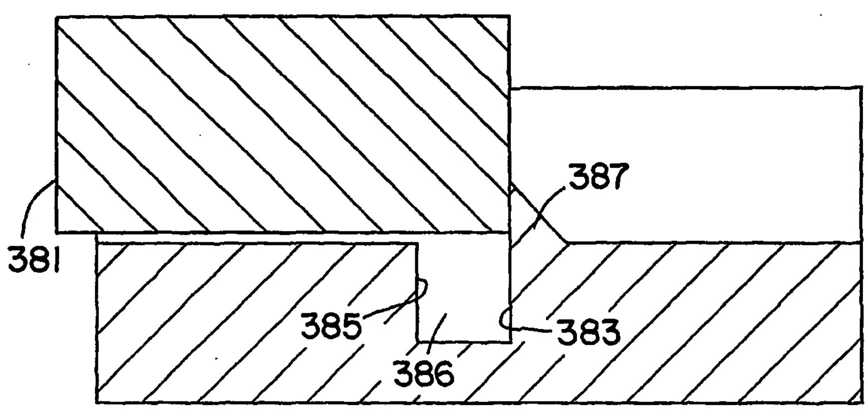

FIG. 39B

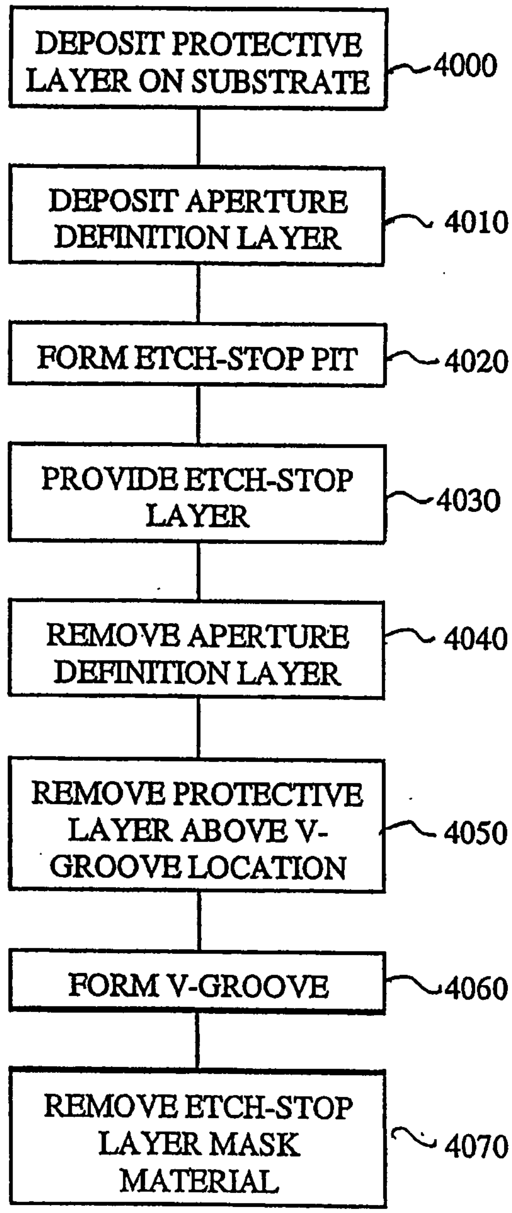
DEPOSIT PROTECTIVE LAYER ON SUBSTRATE
4000
DEPOSIT APERTURE DEFINITION LAYER
4010
FORM ETCH-STOP PIT
4020
PROVIDE ETCH-STOP LAYER
4030
REMOVE APERTURE DEFINITION LAYER
4040
REMOVE PROTECTIVE LAYER ABOVE V-GROOVE LOCATION
4050
FORM V-GROOVE
4060
REMOVE ETCH-STOP LAYER MASK MATERIAL
4070

FIG. 40

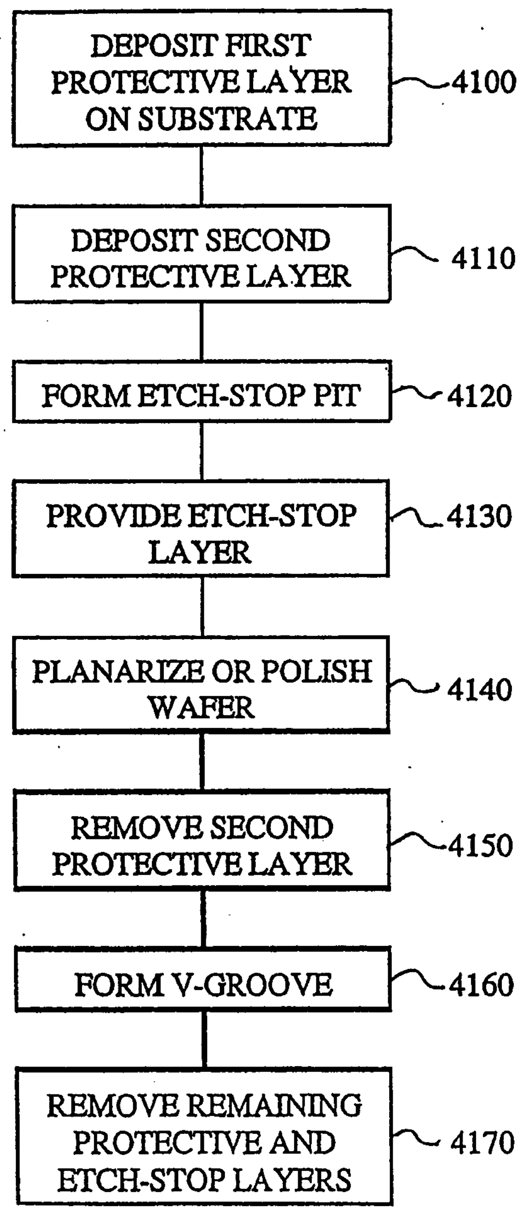
DEPOSIT FIRST PROTECTIVE LAYER ON SUBSTRATE
4100
DEPOSIT SECOND PROTECTIVE LAYER
4110
FORM ETCH-STOP PIT
4120
PROVIDE ETCH-STOP LAYER
4130
PLANARIZE OR POLISH WAFER
4140
REMOVE SECOND PROTECTIVE LAYER
4150
FORM V-GROOVE
4160
REMOVE REMAINING PROTECTIVE AND ETCH-STOP LAYERS
4170

FIG. 41

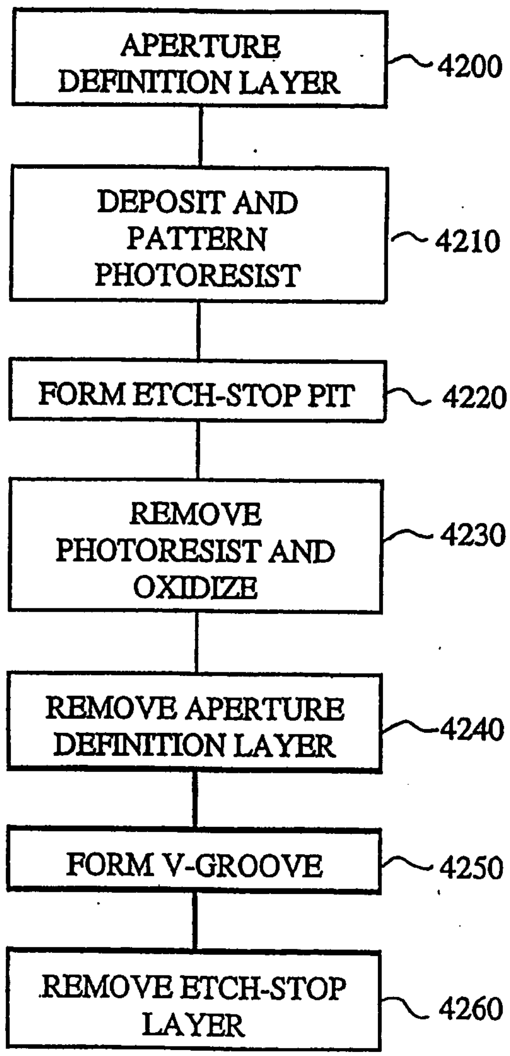
APERTURE DEFINITION LAYER
4200
DEPOSIT AND PATTERN PHOTORESIST
4210
FORM ETCH-STOP PIT
4220
REMOVE PHOTORESIST AND OXIDIZE
4230
REMOVE APERTURE DEFINITION LAYER
4240
FORM V-GROOVE
4250
REMOVE ETCH-STOP LAYER
4260

FIG. 42

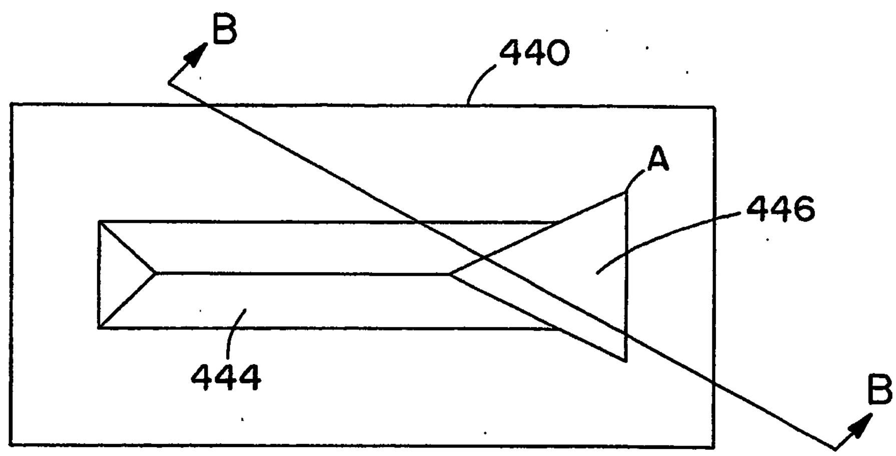

FIG. 43

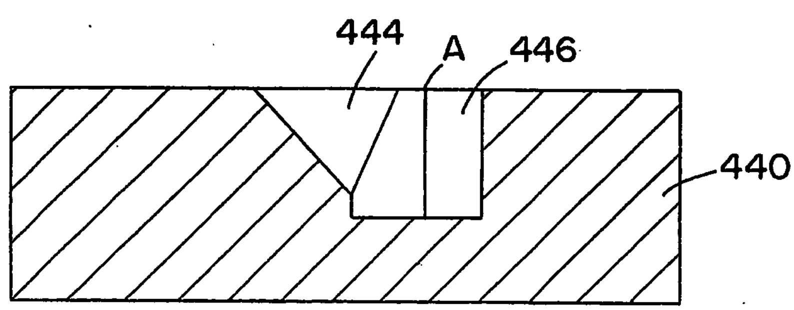

FIG. 44

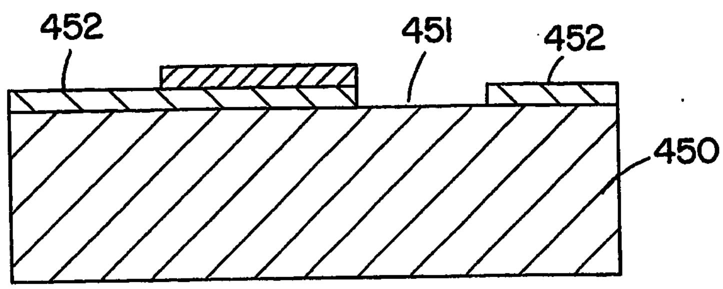

FIG. 45

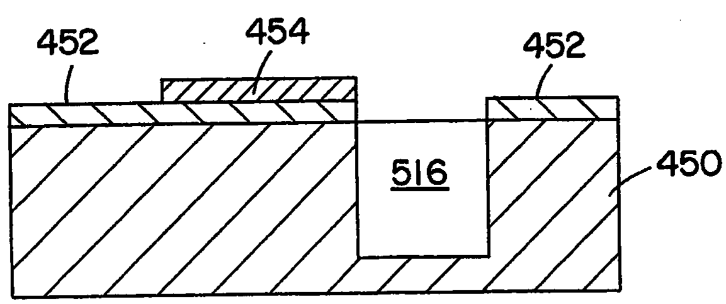

FIG. 46

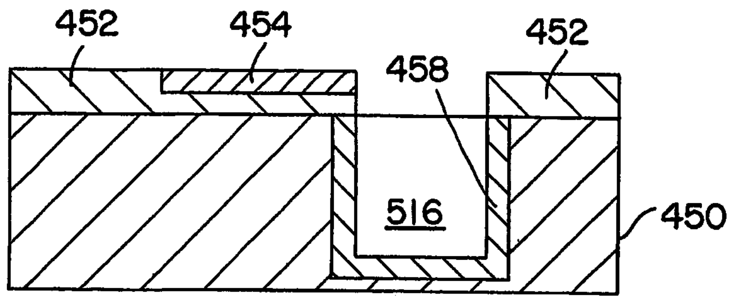

FIG. 47

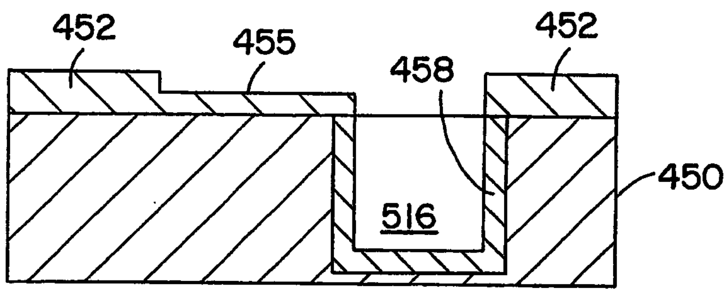

FIG. 48

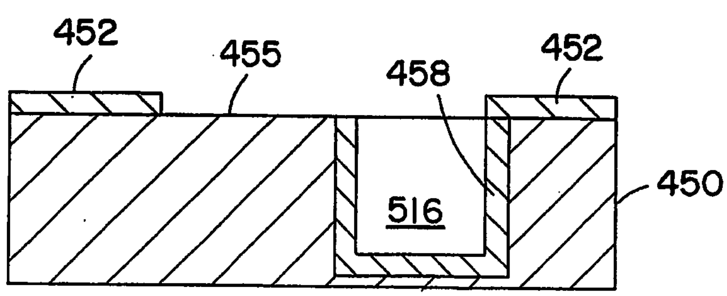

FIG. 49

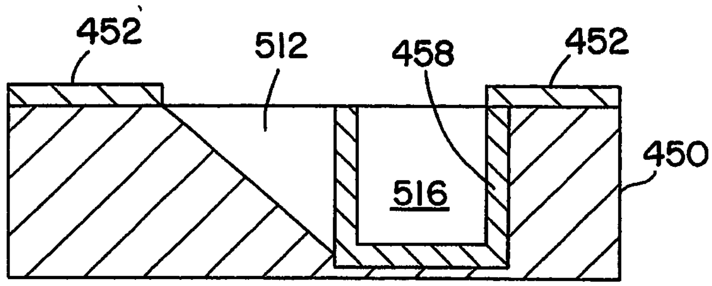

FIG. 50

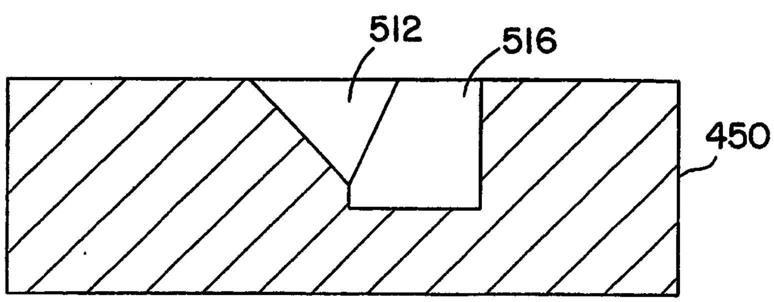

FIG. 51

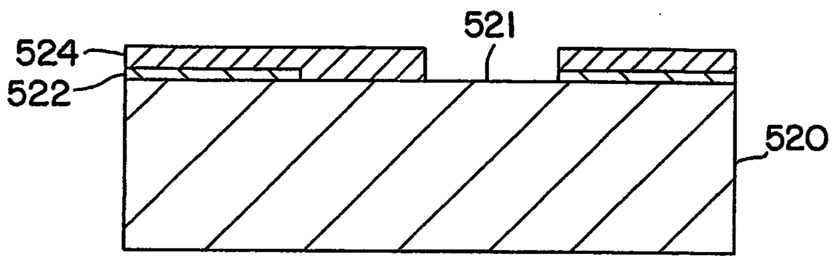

FIG. 52

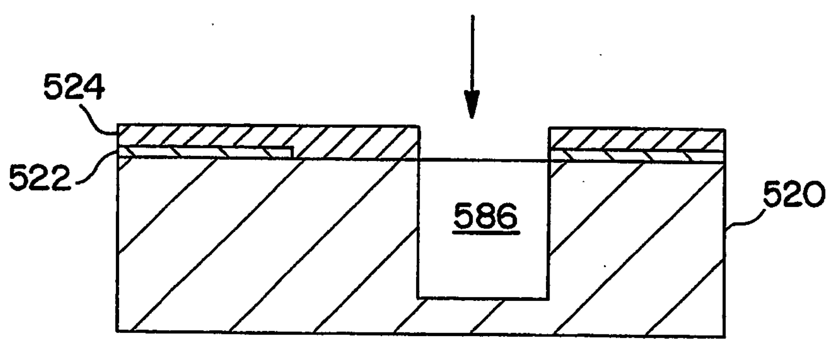

FIG. 53

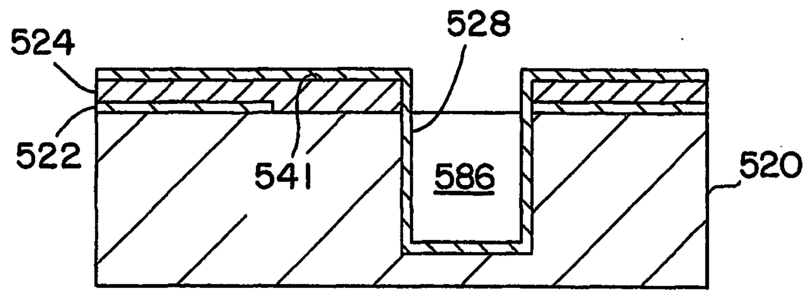

FIG. 54

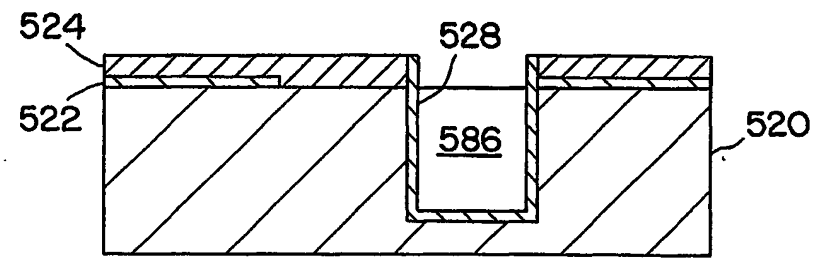

FIG. 55

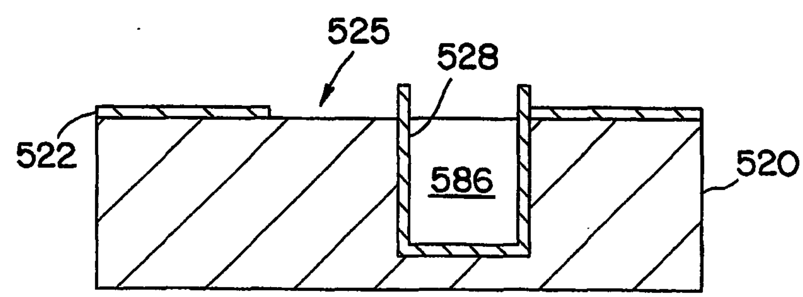

FIG. 56

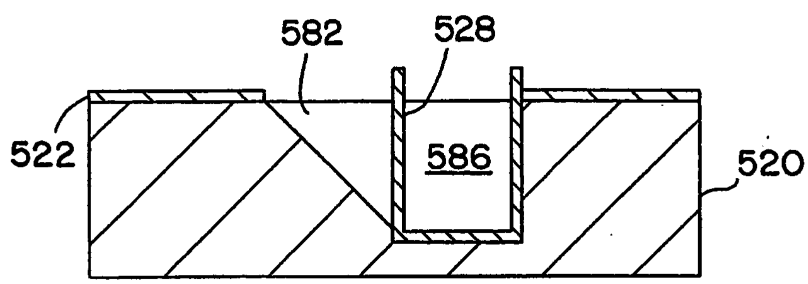

FIG. 57

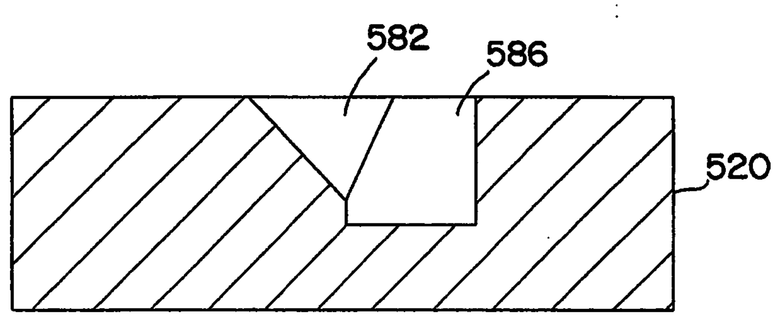

FIG. 58

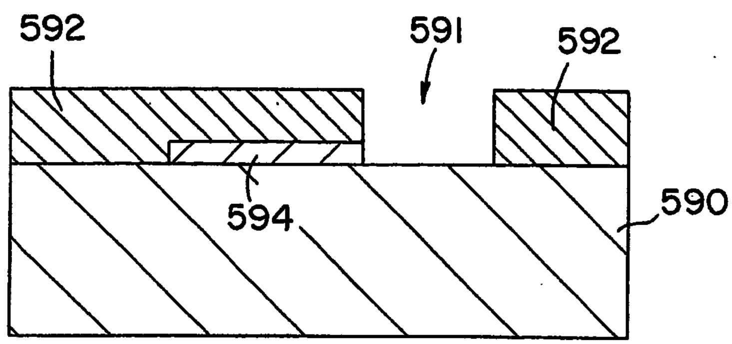

FIG. 59

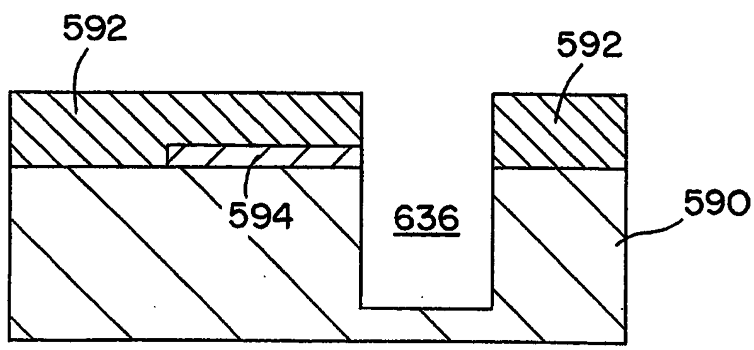

FIG. 60

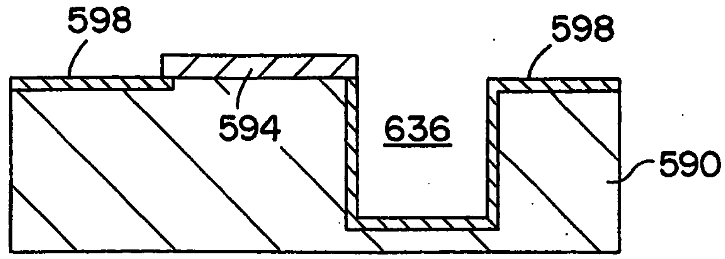

FIG. 61

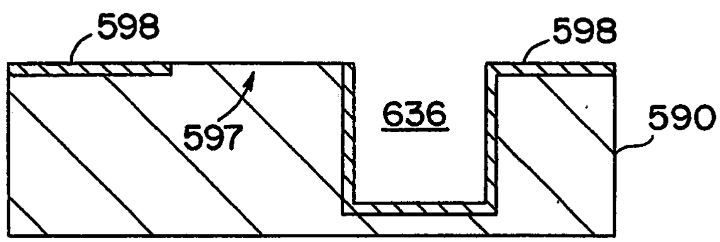

FIG. 62

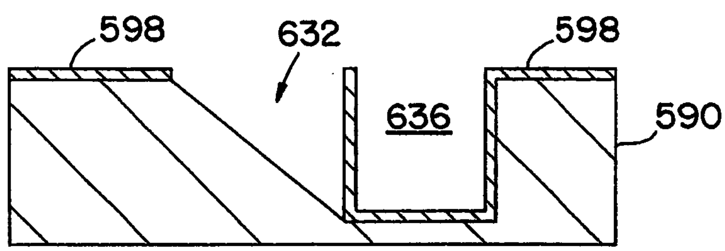

FIG. 63

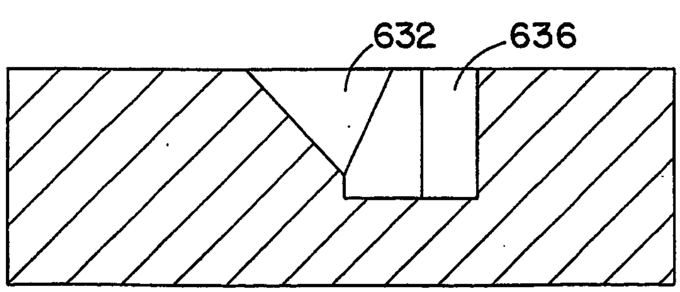

FIG. 64